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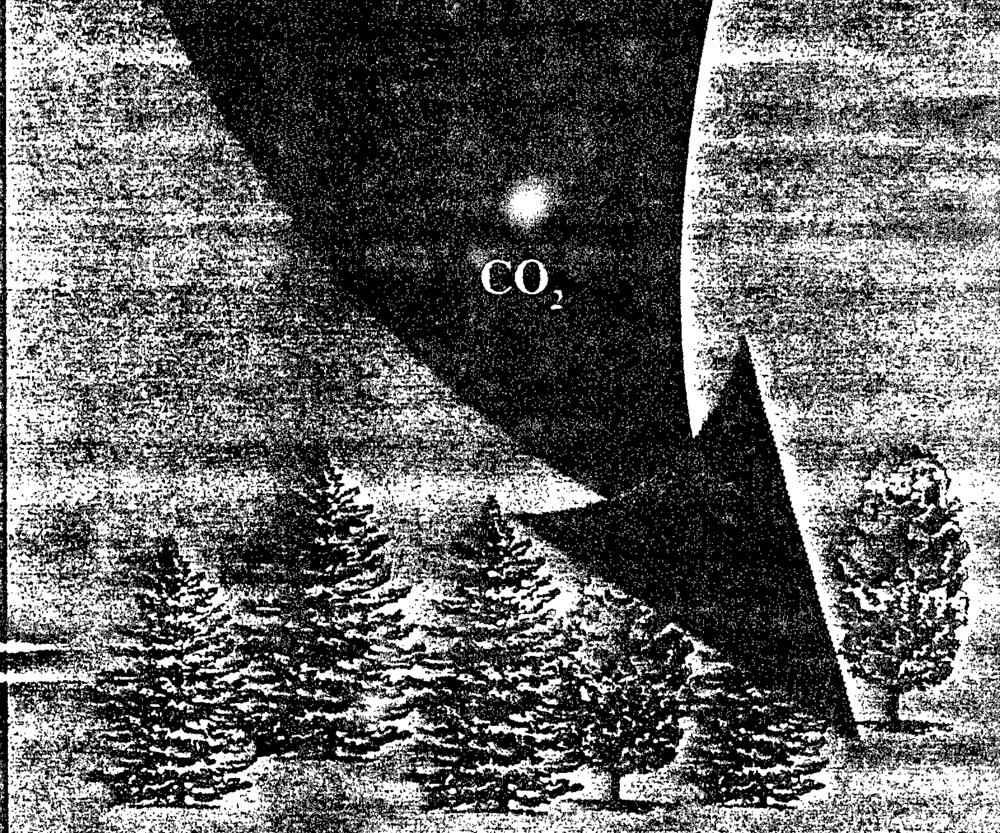
CARBON SEQUESTRATION AND FOREST MANAGEMENT AT DOD INSTALLATIONS: AN EXPLORATORY STUDY



CARBON SEQUESTRATION AND FOREST MANAGEMENT AT DOD INSTALLATIONS: AN EXPLORATORY STUDY

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DISCLAIMER

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Executive Summary

Scientific assessments carried out by the Intergovernmental Panel on Climate Change show that carbon dioxide (CO_2) and other radiatively important trace gases (RITGs) such as methane (CH_4) are increasing in the atmosphere and may result in a rapidly changing climate with increased temperatures and altered precipitation patterns (IPCC 1990, 1992). A rapidly changing climate could adversely impact forest vegetation composition, structure, and productivity resulting in widespread forest dieback and the redistribution of forest vegetation to regions with favorable climates. One policy option for offsetting the increase of atmospheric CO_2 and mitigating a rapidly changing climate is carbon sequestration and conservation by forest vegetation and soil (Schwengels et al. 1990, National Academy of Science 1991, Dixon et al. 1994). Forests located on U.S. Department of Defense (DOD) training installations throughout the United States offer promising opportunities to sequester and conserve atmospheric carbon because many lands could be reforested, other lands could receive management practices that would improve tree growth, while additional lands support mature forests that are vast carbon reservoirs (American Forestry Association 1992).

The DOD manages approximately 12.3 Mha of land throughout the United States (American Forestry Association 1992). Of this, an estimated 2.4 Mha are forest that are used mainly for carrying out realistic training missions for troop preparedness. In many instances, the stress from tactical vehicles and combat training have degraded the usefulness of forests for military purposes. Consequently, the DOD has established programs targeted to improve or maintain the environment on lands under its jurisdiction. The Strategic Environmental Research and Development Program (SERDP) is one program charged to address concerns that include global environmental change and ecological restoration through research and technology development to improve the environmental quality of military installations. This research was conducted under the auspices of SERDP.

The primary purpose of this report is to explore the influence of management practices such as tree harvesting, deforestation, and reforestation on carbon sequestration potential by DOD forests by performing a detailed analysis of a specific installation. Camp Shelby, Mississippi was selected for analysis because (1) it is a large installation within a prime forestry area, (2) it has been degraded by military training, and (3) its forests are managed by the U.S. Forest Service (FS) so forest-stand data are available for analysis. The specific research goals were (1) to quantify forest carbon pools and flux at Camp Shelby from 1990 through 2040, (2) to evaluate carbon sequestration as influenced by hypothetical management scenarios, and (3) to account for on-site and off-site carbon benefits.

Carbon pool estimates were based on Camp Shelby's forest-stand area, age class, and stocking level. A stand-level carbon budget was developed for each of the three major forest types based on growth and yield tables from the Aggregate Timberland Assessment System (ATLAS), a

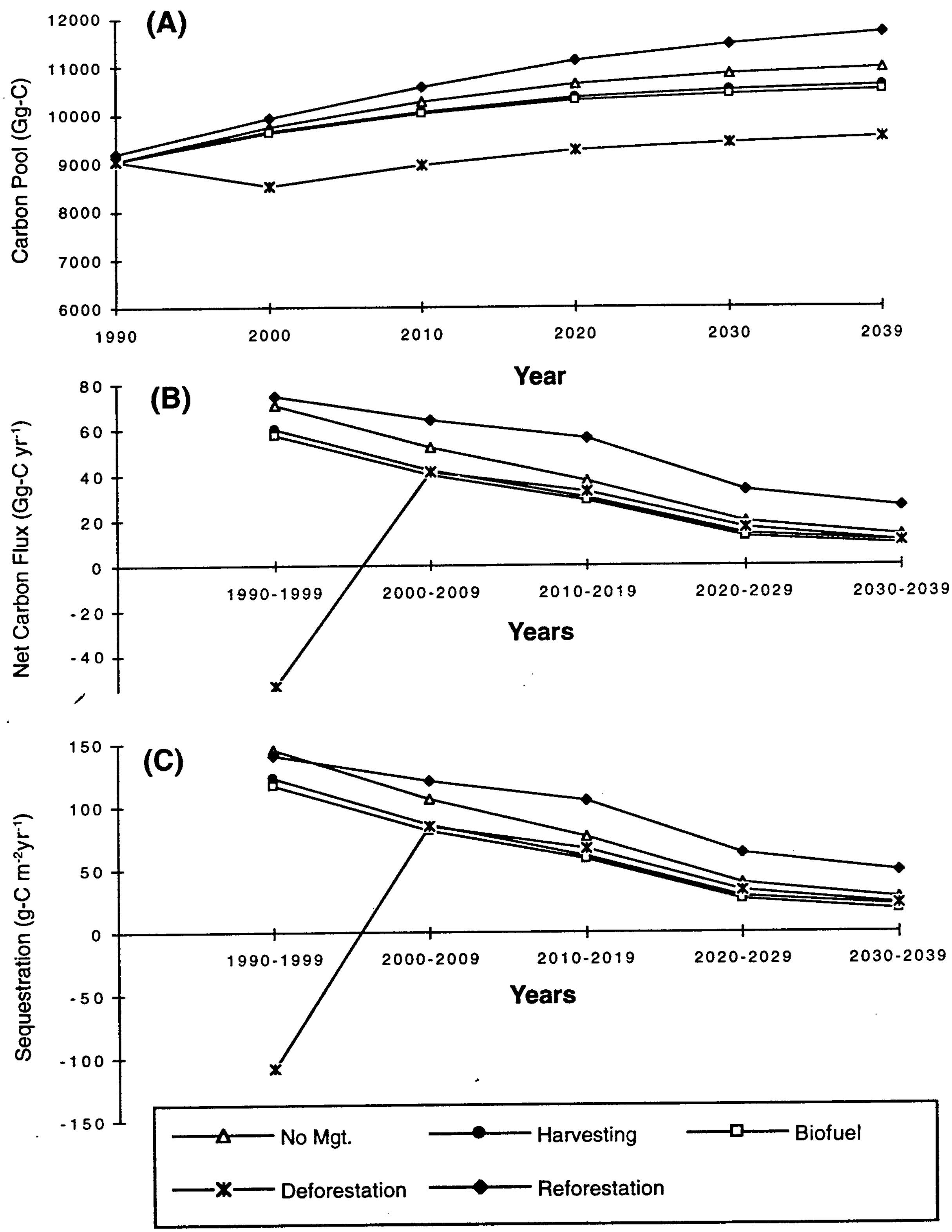


Figure 1. A comparison of (A) total carbon, (B) net carbon gain, and (C) carbon sequestration rate of Camp Shelby forests as influenced by five hypothetical management scenarios. Positive and negative values are respectively net carbon gain or loss.

timber inventory model developed by the FS (Mills and Kincaid 1992). Each carbon budget specified the density of carbon (kg-C m^{-2}) within each carbon pool (live tree, soil, forest floor, understory, vegetation, woody debris) for each age class (Turner et al. 1993). Carbon pools were then calculated by taking the product of the land area of the inventory and the carbon densities from the stand-level carbon budgets.

Flux is the transfer of carbon among the forest pools and the atmosphere in either direction, and carbon loss due to harvesting. Net flux is the average annual change in the total carbon pool since the previous decade, and was calculated by dividing the difference of the ending and beginning carbon pools by 10 years.

Five different hypothetical management scenarios were simulated to assess their consequences on forest carbon pools and flux from 1990 through 2040. Scenario 1 (no-action) was an assessment of carbon dynamics for the year 1990 and then projected to the year 2040 with no forest management action such as harvesting or reforestation. This scenario was the benchmark for comparison with the others. Scenario 2 (harvesting) assumed that commercial tree harvesting occurred at a rate defined as normal management by the FS, Black Creek Ranger District which includes Camp Shelby (Department of the Army 1991). Scenario 3 (biofuel) assumed that trees were harvested to support a biofuel program for Camp Shelby as proposed for many DOD installations by the American Forestry Association (1992). Scenario 4 (deforestation) assumed that deforestation of 8,593 ha was necessary to develop new training areas and maintenance facilities during the 1990s (Department of the Army 1991). Scenario 5 (reforestation) assumed that 4,050 ha of previously harvested land were reforested during the 1990s (Department of the Army 1991)

Management action profoundly affected the carbon pools and sequestration potential of Camp Shelby's forests as simulated during the 50-year period (Figure 1). Tree harvesting decreased carbon pools and sequestration potential, and reforestation increased carbon pools and sequestration potential. Tree harvesting at the rate defined as normal management (scenario 2), resulted in a smaller total carbon pool in 2040 and a 25% loss in the rate of carbon sequestration compared with scenario 1. Deforestation of 8,593 ha resulted in a reduction of total carbon and a 96% loss in on-site carbon sequestration potential. The reforestation of 4,050 ha of land significantly increased carbon storage and resulted in a 29% increase in the rate of on-site carbon sequestration during the 50 years. Thus, management practices that promote reforestation and discourage deforestation will provide the maximum carbon sequestration and conservation. Potential ancillary benefits include enhanced wildlife habitat, increased biodiversity, decreased soil erosion, and improved water quality.

Under the harvesting, biofuel, and deforestation scenarios, harvested wood was assumed to be transferred off-site for production of lumber or fuelwood. Long-term wood products and fuelwood can provide a benefit in offsetting the built-up of atmospheric carbon (Table 1). The lumber that is used in construction projects provides long-term carbon storage. Even when lumber is discarded into landfills it will retain its carbon for many more years. Harvesting trees to support a biofuel program also provides a carbon benefit in that fossil fuel is displaced with

Table 1. Carbon benefits of Camp Shelby forests during 10-year (2000-2009) and 50-year (1990-2040) periods as affected by five hypothetical management scenarios.								
Management Scenario	Net On-site Carbon Sequestration		On-site Carbon Benefit[a]		Off-site Carbon Benefit[ab]		Combined Carbon Benefit[a]	
	(Gg-C yr^{-1})							
	10-year	50-year	10-year	50-year	10-year	50-year	10-year	50-year
No-action	52	39	0	0	0	0	0	0
Harvesting	42	31	-10	-8	2.6	2.6	-7.4	-5.4
Biofuel	40	30	-12	-9	10.1	10.1	-1.9	+1.1
Deforestation	41	10	-11	-29	12.2	4.9	+1.2	-24.1
Reforestation	64	51	+12	+12	0	0	+12.0	+12.0

[a] Compared with the no-action scenario.
[b] Assumes a 0.4 and 0.9 conversion efficiency to long-term wood products/landfill and biofuel energy production, respectively, for C transferred off-site.

modern, fuelwood technology. The ideal situation is where carbon emissions from energy production approximates carbon sequestration by the trees that will eventually become fuelwood. Consequently, an equilibrium in carbon flux between energy production and tree sequestration is eventually established.

Under the Climate Change Action Plan the United States is committed to reduce RITG emissions to their 1990 levels by the year 2000 (Clinton and Gore 1994). If Mississippi were to adopt the Action Plan as a state goal, then 3,640 Gg-C yr^{-1} of emission reductions or offsets would be required. Reforestation of Camp Shelby (scenario 5) could provide 0.3% of the necessary offsets during the 2000-2009 decade.

1.0 INTRODUCTION, SCOPE OF WORK, AND POLICY BACKGROUND

1.1 Introduction

Scientific assessments carried out by the Intergovernmental Panel on Climate Change (IPCC) show that carbon dioxide (CO_2) and other radiatively important trace gases (RITGs) such as methane (CH_4) and nitrous oxide (N_20) are increasing in the atmosphere and may result in a rapidly changing climate with increased temperatures and altered precipitation patterns (IPCC 1990, 1992). A rapidly changing climate could adversely impact forest vegetation composition, structure, and productivity resulting in widespread plant dieback and the redistribution of forest vegetation to regions with favorable climates. One policy option for offsetting the increase of atmospheric CO_2 is carbon sequestration and conservation by forest vegetation and soil (Schwengals et al. 1990, National Academy of Science 1991, Dixon et al. 1994). Forests located on U.S. Department of Defense (DOD) training installations throughout the United States offer promising opportunities to sequester and conserve atmospheric carbon because many lands could be reforested, other lands could receive management practices that would improve tree growth, while additional lands support mature forests that are vast carbon reservoirs (American Forestry Association 1992).

The U.S. Environmental Protection Agency (EPA) has been evaluating potential changes in climate that may result from increasing atmospheric RITGs and addressing mitigating options that could reduce the threat of elevated RITG concentrations (e.g., Smith and Tirpak 1989, Lashof and Tirpak 1990, Dixon et al. 1991, Turner et al. 1993). These reports recommend management practices to improve the potential for natural forests, tree plantations, and urban trees to sequester and conserve atmospheric carbon. Such action could include increasing the growth of forest stands through practices such as tree thinning, the reforestation of marginal croplands, and encouraging urban tree plantings throughout the United States (Sampson 1993). A recent publication jointly sponsored by the EPA, DOD and the American Forestry Association (AFA) assessed management options to improve carbon sequestration and conservation on military installations through improved management of existing forests, reforestation of degraded lands, and landscaping cantonment areas with trees (American Forestry Association 1992). The research reported herein evaluated the influence of management practices on carbon dynamics at a specific facility. The research is of value to installation commanders and land managers as they plan the management of DOD forests in conjunction with military training.

The DOD manages approximately 12.3 Mha of land throughout the United States (American Forestry Association 1992). Of this, an estimated 2.4 Mha is forest that is used mainly for carrying out realistic training missions for troop preparedness (Figure 1). In many instances, the stress from tactical vehicles and combat training have degraded the usefulness of forests for military purposes. In addition, military training has caused the destruction of vegetation cover and soil erosion. Consequently, DOD has established programs targeted to improve or

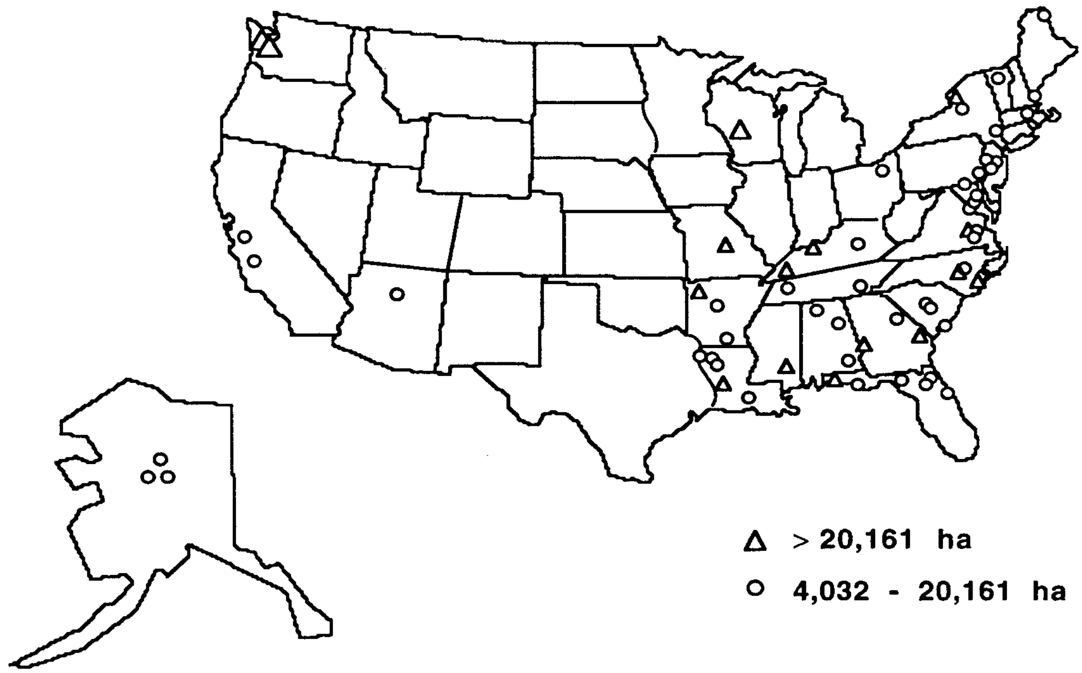


Figure 1. Military installations within the United States with more than 4,032 ha of forestland. Data are from the American Forestry Association (1992).

maintain the environment on lands under its jurisdiction. The Strategic Environmental Research and Development Program (SERDP) is one program charged to address concerns that include global environmental change and ecological restoration through research and technology development to improve the environmental quality of military installations. This research was conducted under the auspices of SERDP.

1.2 Scope of Work

The primary purpose of this report is to explore an approach at a specific military installation for evaluating the influence of forest management on the carbon sequestration potential of DOD forests. Section 2 provides background information on climate change, vegetation, and carbon cycles. Section 3 is the detailed analysis of five hypothetical forest-management scenarios including no-action, tree harvesting, biofuel, deforestation, and reforestation. Camp Shelby, a tactical-vehicle training installation in Mississippi, was selected for the exploratory study because (1) it is a large installation in a prime forestry area, (2) it has been physically degraded by training activities, and (3) its forests are managed by the U. S. Forest Service (FS) so that stand inventory data are available. The approach used to quantify carbon dynamics was to link the forest-stand inventories with stand-level carbon densities to calculate current and future carbon pools and fluxes (Turner et al. 1993). The specific research goals were (1) to quantify forest carbon pools and flux at Camp Shelby from 1990 through 2040, (2) to evaluate carbon sequestration as influenced by various hypothetical management scenarios,

and (3) to account for on-site and off-site carbon benefits. Section 4 presents management practices that may improve the potential for carbon sequestration and storage by DOD forests throughout the United States. Conclusions of the research are presented in Section 5.

1.3 Policy Background

The Climate Change Action Plan (CCAP) commits the United States to reducing RITGs to their 1990 levels by the year 2000 (Clinton and Gore 1994). This means implementing a combination of reduced emissions and increased carbon sinks amounting to approximately 7% of the 1990 rate, or 106 Tg-C equivalent for all gases combined. Carbon emissions for the years 1990 (in the absence of a RITG-reduction policy) and 2000 in the United States are estimated to be 1,462 and 1,568 Tg-C, respectively. Managing DOD forests to optimize carbon sequestration can contribute to achieving the 7% reduction.

2.0 BACKGROUND: CLIMATE CHANGE, VEGETATION, AND CARBON BUDGETS

2.1 Climate Change

Rising levels of atmospheric CO_2 (Figure 2) and other RITGs (e.g., CH_4, N_2O) from anthropogenic activity (e.g., fossil-fuel combustion, deforestation, industrial emissions) are likely to induce changes in the earth's climate over the coming decades (IPCC 1990, 1992). Even though considerable uncertainty remains about the rate and magnitude of the possible climate change, there is an emerging consensus that policies relevant to stabilizing or reducing the level of atmospheric CO_2 and other RITGs should be explored (National Academy of Science 1991, Rubin et al. 1992). One option that shows considerable promise is to increase the potential for forest vegetation and soil to sequester atmospheric carbon and conserve it for long periods of time (Houghton et al. 1993, Wisniewski et al. 1993, Dixon et al. 1994).

The relationship between increased concentration of RITGs in the atmosphere and observable changes in climate and potential ecological effects have been the subject of numerous investigations and much debate. Global circulation models cannot accurately predict the magnitude and timing of changes in climate on regional scales, but a widely viewed estimate is that average surface atmosphere temperatures will increase by 1.5-4.5°C within the next few decades (Schneider et al. 1992, Shugart 1993). Temperature changes of this magnitude have occurred in past geological times, such as in the current interglacial period after the last ice age (Table 1). However, a change in climate of this magnitude and occurring in a few decades rather than over millennia may have dramatic effects on forests and agricultural productivity, sea levels, water resources, and human health (National Academy of Science 1991, Peters and Lovejoy 1992).

2.2 Potential Consequences of Climate Change to Vegetation

The consequences of a rapidly changing climate will have both direct and indirect effects on forest systems (Smith 1992, Smith et al. 1992, King 1993, Smith and Shugart 1993). The main effect could be the redistribution of vegetation (Webb 1992, Grabherr et al. 1994). The reconstruction of past warming and cooling periods from the paleoecological record demonstrates that vegetation distributions varied significantly from those of today. For example, vegetation in the northern hemisphere has migrated northward or southward in response to warming or cooling periods, respectively. During the ice age that ended 10,000 years ago, Arctic tundra extended into the Great Lakes region and northern spruce trees grew as far south as Georgia and Texas. During the most recent warming period approximately 6,000 to 9,000 years ago when the atmosphere was 1.5°C warmer than at present, many North American plant associations shifted approximately 300 km northward.

In addition to the paleoecological record, plant distribution models have been used to predict the breakup and reassortment of future vegetation associations. Davis and Zabinski (1992) project that a global warming of approximately 3°C would cause the demise of sugar maple, beech, yellow birch, and hemlock from the

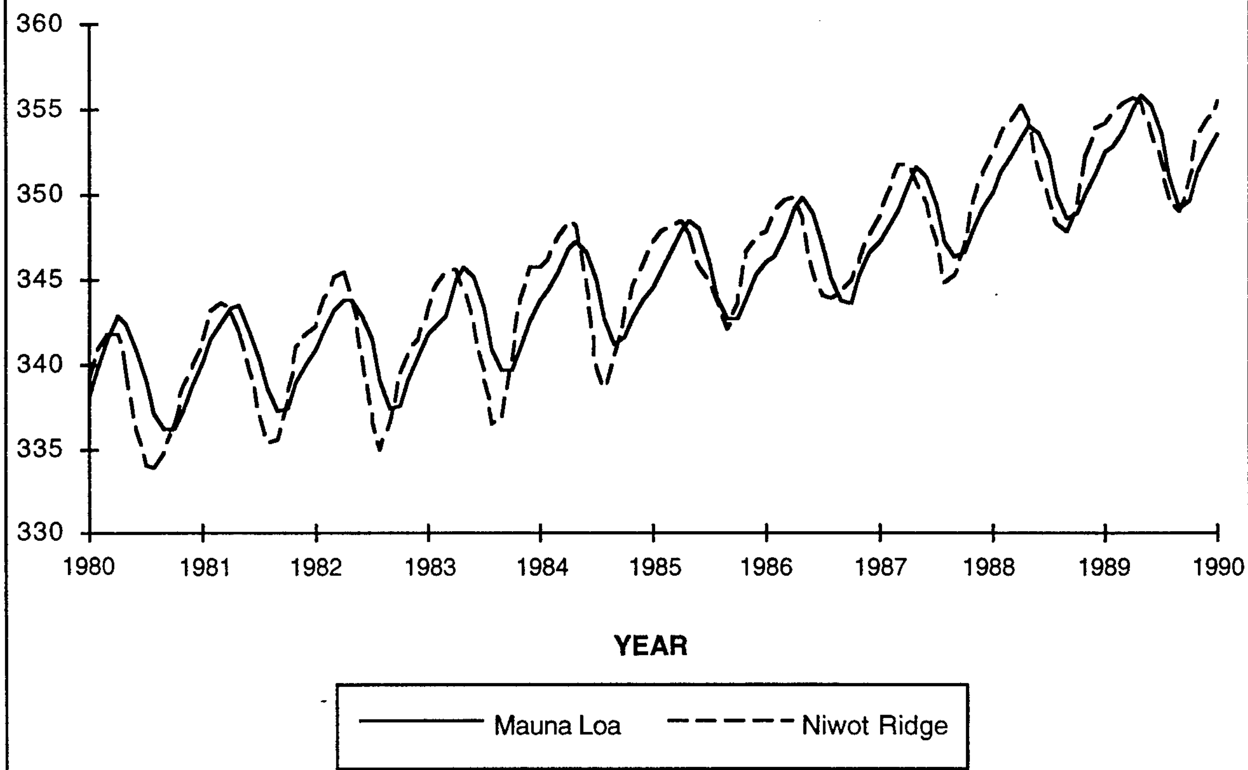


Figure 2. Concentrations of atmospheric CO_2 measured at Mauna Loa, Hawaii and Niwot Ridge, Colorado. Data are from Boden et al. (1991).

Table 1. Past and predicted future rates of temperature change. Data are from Hinkley and Tierney (1992).

Time Period	Warming (°C)	Rate (°C/century)
15,000 BP (Last Glacial) to 11,500 BP Allerod)	10	0.3
10,500 BP (Younger Dryas) to 7,000 BP (Climatic Optimum)	7	0.2
5000 BP to 2,500 BP	4	0.2
Last 10,000 years	5	0.05
Last 100 years	0.5	0.5
Next 100 years	2.5	2.5
Next 100 years (High Latitudes)	5	5

southern parts of their ranges in the eastern United States. A subsequent northern shift of several hundred kilometers in the species distribution of these ranges would then occur.

The explanation for changes in vegetation distribution during warming and cooling periods is that plant processes such as photosynthesis, respiration, flower and seed set, seed germination and seedling establishment occur optimally within specific temperature and soil-water ranges (Barker et al. 1991, Woodward 1992). Species respond individually to temperature and soil water conditions. Above or below the optimum, plant growth, development, and reproduction will suffer depending on the magnitude of departure from the norm. An increase in the growing season will allow plants greater time to complete life cycles with increased biomass production. However, drier soil conditions in some regions may offset the longer, warmer, growing season by reducing seed production and seedling establishment. Furthermore, increases in temperature over long periods may be detrimental to cool-season species because they require cold temperatures for flowering, seed set, or seed germination to occur. Therefore, cool-season plants may migrate northward or to a higher elevation to be associated with favorable temperatures conducive with phenological requirements (Peters and Darling 1985, Grabherr et al. 1994).

The ability for plant species to migrate to new areas with suitable climatic zones will depend mainly on propagule dispersal mechanisms and the presence of physical barriers. According to Davis and Zabinski (1992), the average migration rate for North American tree species is about 20 to 40 km per century. This rate of migration is much too slow to track a rapidly changing climate. In addition, barriers such as roads, cities and agricultural fields will present obstacles to vegetation migration (Myers 1992).

The indirect effects of a rapidly changing climate on forest vegetation will probably include increased insect and other pathogen outbreaks, and increased fire frequency and intensity (Franklin et al. 1991, Smith 1992). Insect and pathogen outbreaks may increase because they are usually associated with extreme weather patterns and forest dieback. Both causal agents will be common with a rapidly changing climate. In addition, foliage consumption by insects may increase with conditions of warm temperatures and elevated CO_2 (Oechel and Strain 1985, Bazzaz 1990). Forest fire intensity and frequency may also increase with warmer and drier conditions and extensive tree dieback in many areas (Franklin et al. 1991).

2.3 Terrestrial Carbon Budgets

The movement of carbon between the atmosphere and biosphere is known as the global carbon cycle (Figure 3). The biosphere can be further subdivided to include oceans, vegetation, and soil. The general nature of the global carbon cycle is well documented. However, relatively large uncertainties exist in the magnitude of the various carbon pools and the transfer of carbon among them (Post et al. 1990, Dixon and Turner 1991, Simpson and Botkin 1992, Smith et al. 1993). The oceans store the largest amount of carbon at 38,500 Pg-C ($Pg=10^{15}$ g). Fossil fuels are the second largest carbon pool at 5,000-10,000 Pg-C. The next largest reservoir is soil, estimated at 1,170-1,740 Pg-C. The vegetation and atmospheric pools are the smallest and are estimated at 560-830 and 740 Pg-C, respectively. The annual transfer or flux of atmospheric

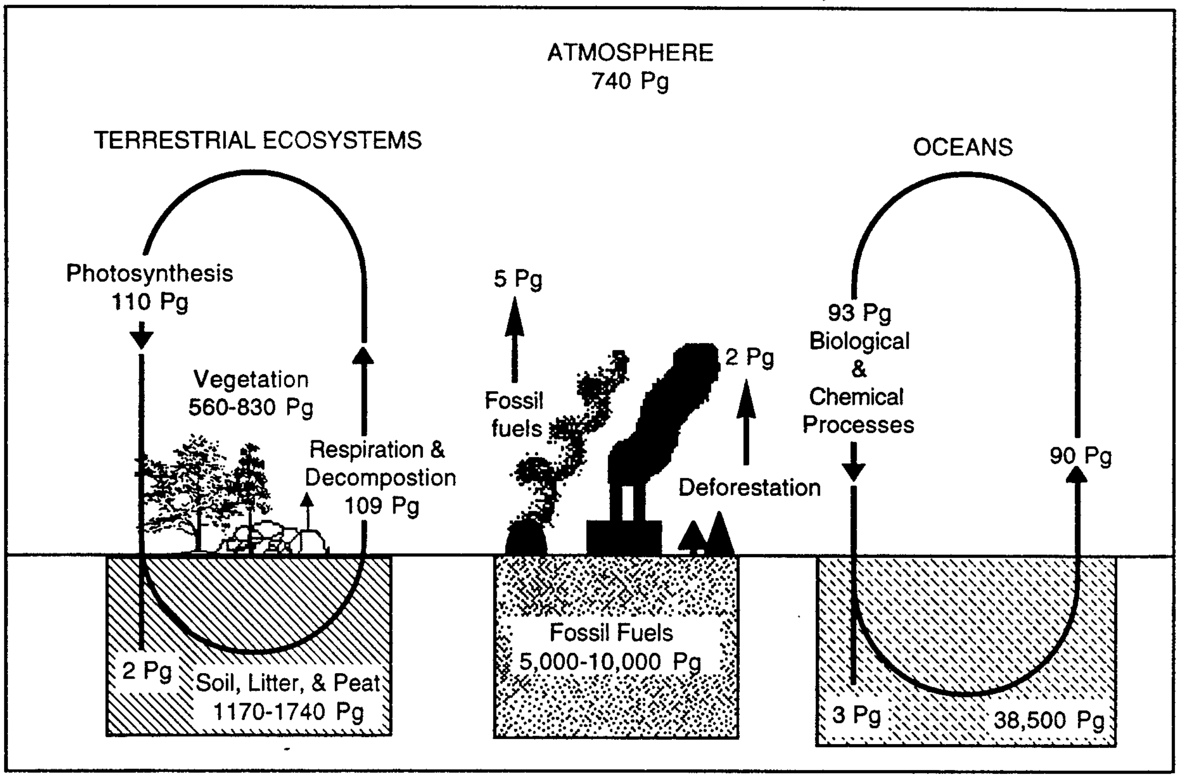


Figure 3. The global carbon cycle.

carbon with the biosphere is about 30%. The flux between the terrestrial biosphere (i.e., vegetation and soil) and atmosphere is about equal to that between the oceans and the atmosphere.

Our understanding of the global carbon cycle suggests that managing terrestrial ecosystems, especially forests, to sequester and conserve carbon may contribute to moderating the rise in atmospheric CO_2 (Sampson and Hair 1992, Wisniewski et al. 1993, Houghton et al. 1993, Dixon et al. 1994). However, better knowledge of forest carbon pools and transfer rates is needed (Box 1). Such information will be crucial in formulating national and international policy to reducing the risks of altering the composition of the atmosphere (National Academy of Science 1991).

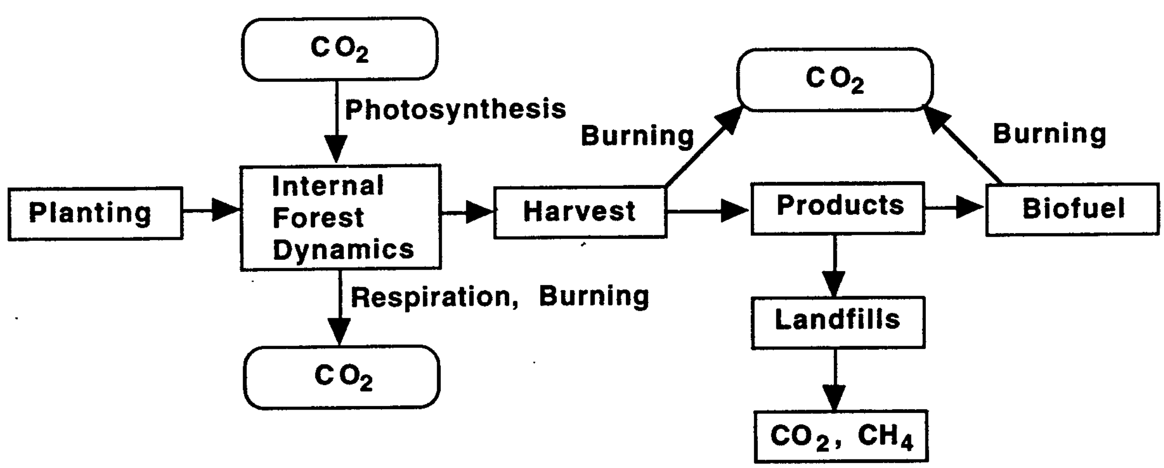
Forest dieback and the redistribution of vegetation to new areas will likely release large amounts of stored carbon into the atmosphere, resulting in a significant positive feedback to climate change (Neilson 1993, Smith and Shugart 1993). Forest vegetation is critical in the carbon cycle because of the processes of photosynthesis, respiration, and decomposition (Woodwell 1992). The rate of photosynthesis is sensitive to many environmental factors such as CO_2 concentration, light intensity, soil water, and soil nutrients. However, photosynthesis is not very sensitive to ambient temperature. On the other hand, the rate of plant respiration and decomposition of organic matter is sensitive to temperature. Temperature changes of a few degrees can increase the rate of respiration by 10-30% while photosynthesis remains approximately constant. Therefore, plant respiration and organic matter decomposition could greatly increase with

Box 1. What Is a Forest-Sector Carbon Budget (from Turner et al. 1993)?

A carbon budget is a bookkeeping system for tracking the amount of carbon in various reservoirs ("pools"), and the amount of carbon transferred among the reservoirs and between the reservoirs and the atmosphere ("flux"). Important carbon pools within forests are trees, other vegetation, soil, the forest floor, and woody debris. "Net flux" is the difference between total uptake into a pool and total output from the pool, and is equal to the change in the pool size during some time interval. Post-harvest use of wood products and landfills are also substantial carbon pools.

The main uptake of carbon into forests is through photosynthesis, the fixation of atmospheric CO_2 by green plants ("primary producers"). Carbon loss from forests is mainly through respiration by green plants and other organisms, through burning, and through harvest of wood by humans. The first two processes result in the direct release of carbon to the atmosphere. The difference between photosynthesis and respiration by green plants is Net Primary Production (NPP). The difference between photosynthesis and respiration by all organisms, including decomposers is the total change in the carbon content of forests due to biological processes (i.e., Net Ecosystem Production, NEP). Thus, NEP is also the net flux of carbon from the atmosphere to the forest from biological processes. The "net accumulation" by forests is NEP minus carbon removed by harvest. The NPP, NEP, and the flux among the carbon pools within the forest, are determined by stand characteristics such as tree species, age class, and site productivity. Regional and national estimates are obtained by combining forest stand NEP estimates with forest inventory data. In contrast, the harvest and reforestation rates are determined by external economic and policy factors.

Unlike the forests, there are no systematic inventories of the product and landfill pools or of the net annual transfer into or out of these pools. The national net change in the pool of forest products in landfills can be estimated as the difference between the amount of forest products transported to landfills and the carbon emissions to the atmosphere from landfills due to forest products.



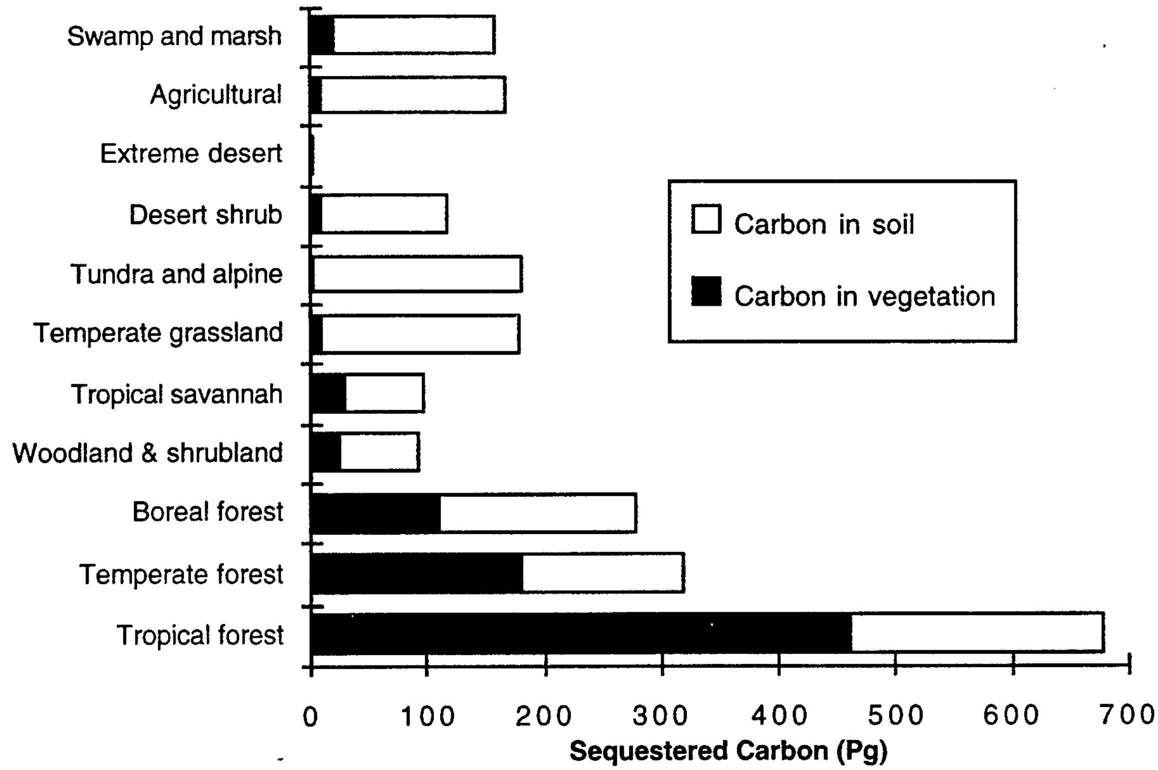


Figure 4. Carbon sequestration in various ecoregions of the world. Data are from Waring and Schlesinger (1985).

global warming and release large amounts of CO_2 and methane into the atmosphere, adding to the problem of anthropogenic emissions.

In contrast, the direct effect of elevated CO_2 on plants might reduce the rate at which CO_2 accumulates in the atmosphere. In controlled environments with elevated CO_2, many plants tend to have increased photosynthesis, decreased respiration, and increased water-use efficiency. However, it is not clear that increased plant growth rates could be sustained by natural vegetation because of soil, water, and nutrient limitations (Luxmoore et al. 1993).

2.4 Forest Management and Carbon Sequestration

Forests are extremely important in the global carbon cycle because they cover approximately 29% of the total land area of the world (World Resource Institute 1990) and store far more carbon than any other terrestrial ecosystem (Figure 4). Furthermore, forests account for a vast amount of the annual carbon flux between the atmosphere and terrestrial sphere (e.g., Apps and Kurz 1991, Kauppi et al. 1992, Turner et al. 1993). Obviously, forest management practices can be extremely important in influencing the carbon dynamics of the terrestrial biosphere (Smith et al. 1993, Winjum et al. 1993). However, according to the World Resources Institute (1990) only about 10% of forests throughout the world are managed to increase tree growth and productivity.

Box 2. Global View of Carbon Conservation/Sequestration (from Turner et al. 1993)

In 1991, a global assessment was undertaken of the potential of forest management practices to store atmospheric carbon (Dixon et al. 1991; Winjum et al. 1993; Dixon et al. 1993; Schroeder et al. 1993). The assessment was based on information on the rates of carbon storage per hectare for many practices, their implementation costs, and estimates of the amounts of land suitable for forest management. Information was compiled through a survey of current published technical literature for forested nations representing boreal, temperate, and tropical regions of the world. Key findings of the assessment are highlighted in the following paragraphs. Because of the geographic scope of the 1991 assessment, it was necessary to use generalized representations of ecoregions and data. Thus, the results are broadly applicable for comparing ecoregions and countries. However, they lack the spatially detailed basis needed for within-country analyses. Also, the data for the 1991 assessment did not consider change over time so that it was not possible to estimate carbon flux.

Carbon Storage

The assessment indicated that the most promising forest management practices to sequester carbon in the terrestrial biosphere include reforestation in the temperate and tropical latitudes, afforestation in the temperate regions, and agroforestry and natural reforestation in the tropics. Least promising from a carbon storage standpoint were the application of silvicultural practices, such as thinning, fertilization and other stand improvement treatments, at all latitudes.

The potential carbon storage ranges of forestation and silvicultural practices by major latitudinal biomes were as follows:

	Forestation	Silviculture
	t-C/ha	
Boreal	15-40	3-10
Temperate	30-180	10-45
Tropical	30-130	14-70

Costs of Storing Carbon

The median cost efficiency for all management practices in terms of establishment costs was about $5/t-C, with an interquartile range (middle 50% of observations) of $1 to $19/t-C. The most cost-efficient forestry and agroforestry practices, based on establishment costs, within zones of latitude are shown in the following table.

Total cost per ton of carbon sequestered, which includes land rental, would be considerably higher. The magnitude of the total cost is difficult to estimate because of economic uncertainties regarding factors such as land rental.

Recent research shows that improved management of temperate forests could sequester considerable amounts of carbon and offset the buildup of atmospheric CO_2 (Box 2). Temperate forests currently cover approximately 600 Mha, about 50% of their potential range. Deforestation during the last two centuries for crop production, pastures and urbanization resulted in these forests being a carbon source. However, with a greatly reduced rate of deforestation and the establishment of new forest stands through plant succession, reforestation, and afforestation, temperate forests are currently a carbon sink (Heath et al. 1993, Turner et al. 1993). Presently, the greatest threat to temperate forests is not deforestation but degradation resulting from poor management practices, soil erosion, air pollution, fire, insects and other pathogens, and wind fall. Improved management must be practiced to minimize these disturbances.

Management practices that could potentially improve carbon sequestration in temperate forests are (Heath et al. 1993, Kauppi and Tomppo 1993):

- reducing the rate of forest degradation and deforestation,
- increasing the rate of reforestation and afforestation,
- implementing practices that stimulate carbon sequestration by forest vegetation and soil, and
- improving the management of post-harvest wood products.

Forest carbon sinks can be greatly expanded by planting additional areas such as marginal cropland with trees and by increasing the growth of existing forest stands (Sampson 1993, Wisniewski et al. 1993). However, trade-offs may exist between high rates of carbon sequestration and large amounts of carbon in wood storage (Heath et al. 1993). Young trees have fast growth rates, but store little carbon. On the other hand, mature forest stands have reduced growth rates, but store large amounts of carbon in woody vegetation and soil. Forest stands must be managed through tree harvesting and reforestation to maximize both carbon sequestration and storage for optimal carbon benefit.

According to Heath and Birdsey (1993) the amount of land in the United States suitable for reforestation is difficult to estimate because of numerous socioeconomic and ecological aspects that need addressing. The potential land base for reforestation in the United States is estimated to be 100 Mha. To encourage reforestation, programs similar to the Conservation Reserve Program or Forests for the Future need to be established (Cubbage 1992, Sampson 1993). These programs provide a carbon sequestration benefit, while also addressing other environmental concerns such as soil erosion and wildlife habitat. The Conservation Reserve Program provided an economic incentive for farmers to establish forest trees on large tracts of environmentally sensitive land and maintain the trees for 10 years. The Conservation Reserve Program resulted in the largest tree-planting effort ever achieved in the United States. Forests for the Future is an international program to encourage large-scale afforestation in less developed countries to offset carbon emissions of the industrialized nations and improve the environment of the cooperating countries. In addition to large-scale efforts, small projects such as planting trees for windbreaks, soil-erosion control, snow guards, improved landscaping, and biofuel plantations are all opportunities to

increase tree numbers and carbon sequestration (Sampson 1993).

Silvicultural practices have proven valuable for improving tree growth on sites with adverse environmental conditions such as limited water or poor soil fertility. These practices can continue to be used to improve the environment for tree growth given a rapidly changing climate (Smith 1992). Such practices include stand thinning, pruning, pest control, irrigation, fertilization, understory plant control, fire management, and harvesting practices. Providing an environment that optimizes tree growth will stimulate carbon sequestration by vegetation and soil and promote long-term storage.

Proper soil management is also crucial to increase carbon sequestration and conservation. Fertile, moist, cool soils provide an environment conducive for carbon storage (Johnson 1992). Consequently, fertilization, mulching, erosion control, and maintaining plant cover are important management tools to encourage soil carbon sequestration and conservation. Frequent tilling and other similar practices that disturb the soil and reduce vegetation cover, promote the loss of carbon through oxidation and erosion (Cole et al. 1993, Kern and Johnson 1993).

The improved management and extensive use of post-harvest wood products can also promote a substantial carbon sink (Heath et al. 1993, Turner et al. 1993). Wood products such as construction lumber and wood furniture provide long-term carbon storage. Therefore, the extensive use of wood products should be encouraged and expanded in the commercial market. The recycling of waste paper and cardboard also provides a conservation of carbon service. However, even with prolonged use, building materials, paper, and cardboard will eventually become waste products and need to be disposed. One option is the use of biofuels to offset the need for fossil fuels (Sampson et al. 1993). Biofuel technology can greatly reduce CO_2 emissions in comparison with fossil fuels (Wright and Hughes 1993, Sampson 1993). An additional benefit is that wood products can still serve as a carbon sink if disposed of in such a manner to minimize CO_2 and methane emissions (Heath et al. 1993).

3.0 CAMP SHELBY: AN EXPLORATORY STUDY OF ATMOSPHERIC CARBON SEQUESTRATION BY FORESTS

Approximately 20% of DOD land within the United States supports forest ecosystems. These lands could make a significant contribution in mitigating increasing atmospheric CO_2 levels through carbon sequestration and conservation (American Forestry Association 1992). Camp Shelby was selected for the exploratory study to illustrate the influence that management and land use can have on carbon sequestration by DOD forests. The management scenarios used for the carbon-sequestration simulations are hypothetical and do not represent planned action by DOD on any military installation.

3.1 Camp Shelby Forests

Camp Shelby is the largest National Guard training installation (land area 56,048 ha) in the United States and is located in southcentral Mississippi near Hattiesburg (Figure 5). Camp Shelby was developed for military training during World War I and is currently a tactical-vehicle training center. The five main vegetation associations are grassland (13%), swamp (< 0.1%), coniferous forest (70%), deciduous forest (7%), and mixed (coniferous and deciduous) forest (10%).

Climatic patterns at Camp Shelby are influenced by weather systems that develop in the Gulf of Mexico (Department of the Army 1991). High humidity, heavy precipitation, and mild temperatures are typical. Average annual precipitation is approximately 1,520 mm and fairly evenly distributed throughout the year. The daily mean temperature is 18.8°C and ranges from 27.4°C in July to 9.1°C in January. Prevailing winds are from the south.

Camp Shelby soils were formed from poorly consolidated sandstone and sediment rock. (Department of the Army 1991). Ultisols are the predominant soil while Alfisols are of secondary importance. The four major soil associations in order of prevalence are:

- McLaurin-Heidel-Prentiss Association (Typic Paleudult-Typic Paleudult-Glossic Fragiudult) is located on gently sloping to steep slopes, and consists of well drained and moderately well-drained sands and loams.
- Benndale-McLaurin-Heidel Association (all Typic Paleudults) is located on gently sloping to steep slopes, and consists of well-drained sands and loams.
- Prentiss-Susquehanna-Falkner Association (Glossic Fragiudult-Vertic Paleudalf-Aquic Paleudalf) is located on sloping lands, and consists of moderately well-drained loamy soils.
- Poarch-Susquehanna-Saucier Association (Plinthic Paleudult-Vertic Paleudalf-Plinthaquic Paleudult) is located on ridge tops and side slopes, and consists of well-drained to moderately well-drained loamy soils.

Most of Camp Shelby lies within the longleaf-slash pine belt of the southern mixed forest, although mixed pine and hardwood forests also

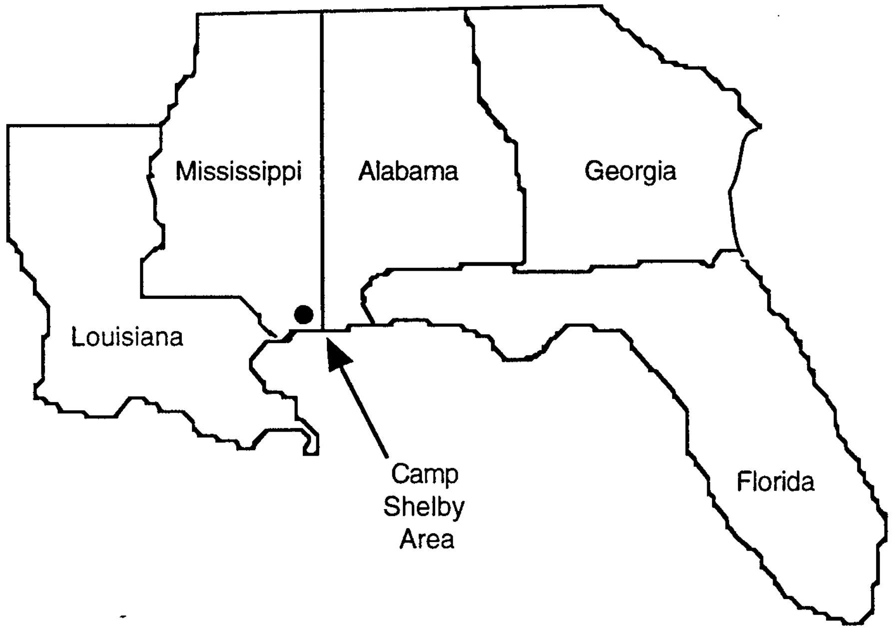


Figure 5. The location of Camp Shelby.

occur (Department of the Army 1991). Longleaf pine grows on the drier, upland sites and slash pine is found on the moist sites. Loblolly pine is found on the moderate to moist sites. These species are generally found in association with other species such as shortleaf pine. Longleaf pine may occur in almost pure stands if the area is frequently burned. On dry sites, longleaf pine may be associated with a sparse mixture of various oak species. Well-drained floodplains and stream terraces support hardwoods including southern red oak, cherrybark oak, white oak, sweet gum, yellow poplar, and hickory. The drainages and bottom lands and floodplain areas that are usually wet are dominated by sweetbay, swamp tupelo, and red maple.

Forestry is the main nonmilitary activity that occurs within the confines of Camp Shelby. The FS, Black Creek Ranger District, DeSoto National Forest (Camp Shelby resides in this District) is managed for longleaf pine, loblolly pine, and slash pine and hardwoods with slash pine and longleaf pine the predominant species (Department of the Army 1991). Most of the forest is managed on an even-aged basis, with rotations of 60, 50, and 40 years, respectively, for longleaf, loblolly, and slash pine. At rotation age, longleaf pine (dry sites) will range from 35 to 51 cm diameter at breast height (DBH) while slash and loblolly pine (moist sites) will range from 30 to 40 cm DBH. Hardwood stands (wet and wetland sites) are managed primarily for wildlife habitat and are seldom harvested. Prescribed burning is used to control understory plant growth and occurs usually on a 5-year cycle in the coniferous forest. Site preparation (e.g., chemical, mechanical, fire) is used to promote development of new tree stands in a cut area and reduce competition for commercial species.

Table 2. Forest age-class distribution by land area for Camp Shelby forests.[a]

Age Class (years)	Forest Type (hectares [%])		
	Coniferous	Deciduous	Mixed
5 - 10	262 (1)	< 1 (< 1)	60 (1)
10 - 20	4,165 (8)	337 (7)	136 (3)
20 - 30	3,521 (10)	195 (6)	422 (8)
30 - 50	14,359 (38)	1,049 (26)	1,813 (43)
50 - 70	16,163 (41)	2,211 (53)	2,768 (39)
70 - 100	943 (20)	151 (8)	384 (6)

[a]Data Source: U.S. Department of Agriculture Forest Service, Black Creek Ranger District.

3.2 Methods Used to Evaluate the Carbon Dynamics of Camp Shelby

Carbon Pools

Carbon pool estimates were based on forest-stand area, age class, and stocking level (Table 2). A stand-level carbon budget was developed for each of the three major forest types of Camp Shelby (Figure 6) based on growth and yield tables from the Aggregate Timberland Assessment System (ATLAS), a timber inventory model developed by the FS (Mills and Kincaid 1992). Each carbon budget specified the density of carbon (kg-C m^{-2}) within each carbon pool (live tree, soil, forest floor, understory, woody debris) for each age class using an approach similar to that developed by Turner et al. (1993). Carbon pools were then calculated by multiplying the land area of the inventory and the carbon densities from the stand level carbon budgets. Partitioning among the various carbon pools was determined as follows:

Tree carbon pool. The ATLAS growth and yield tables include only growing stock volume for commercial trees. To account for non-commercial species an adjustment factor of 1.01 and 1.14 for softwoods and hardwoods, respectively, was applied (Thompson 1989). The growing stock volume was then converted to whole tree carbon based on the relative proportion of hardwood and softwood volume (Cost et al. 1990, Harmon 1993). Carbon from sapling trees (< 12.5 cm DBH) was also included and estimated according to the biomass statistics developed by Cost et al. (1990). The tree pool accounts for leaves, twigs, limbs, bole, and coarse roots. A full tree stocking level was assumed for the simulations.

Understory carbon pool. The carbon pool size for understory vegetation was estimated based on data presented by Birdsey (1992). Understory vegetation usually grows rapidly after tree harvesting or other disturbances such as fire but then slows with subsequent tree growth and canopy closures. Understory vegetation growth again increases as the forest

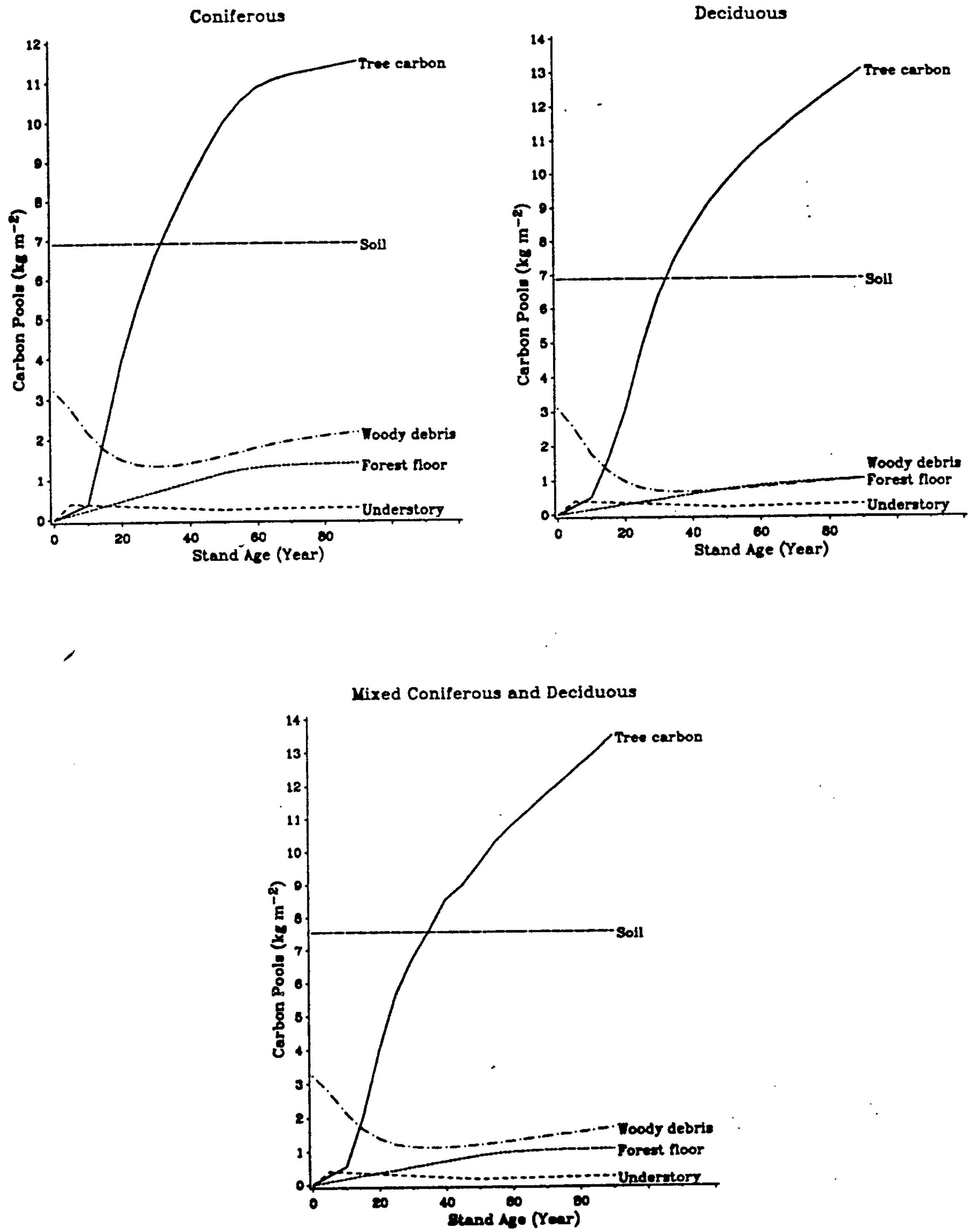


Figure 6. Stand-level carbon budgets for the coniferous, deciduous, and mixed forests of Camp Shelby.

stand matures and canopy gaps occur from tree fall.

Woody debris carbon pool. A modeling approach developed by Harmon (1993) was used to estimate age-specific carbon pools. The woody debris pool consists of standing dead trees, dead coarse roots (> 2 mm diameter), and dead woody material (> 2 cm diameter) lying on the forest floor.

Forest floor carbon pool. Estimates of initial forest floor carbon and the age-specific increases in pool size were based on data provided by Vogt et al. (1986) and evaluated by Plantinga and Birdsey (1993). The forest floor component is composed of dead plant material lying on the soil surface that cannot be classified as woody debris.

Soil Carbon Pool. The starting level for mean soil carbon in the model simulations was derived from Kern (199~~4~~5) and was 7.0, 7.0, and 7.8 kg-C m^{-2} to a one meter depth for the coniferous, deciduous, and mixed forests, respectively. Soil carbon was assumed to be constant over the course of stand development based on research conclusions of Johnson (1992) for all simulations except for the deforestation scenario that is described later.

Carbon Flux

Flux is the transfer of carbon between the forest and the atmosphere in either direction, and carbon loss due to harvesting. Net flux is the average annual change in the total carbon pool since the previous decade, and was calculated by dividing the difference of the ending and beginning carbon pools by 10 years. Fire is an important management tool in the coniferous forest (Department of the Army 1991); however, a separate estimate of fire emissions was not attempted since all mortality was transferred to the woody debris pool (Turner et al. 1993).

Forest Management Scenarios

Five hypothetical forest management scenarios were simulated to assess their consequences on carbon pools and flux from 1990 through 2040.

Scenario 1 (no-action) assumed no active management such as harvesting or reforestation occurred during the years 1990 to 2040. Scenario 1 was the benchmark to which the other scenarios were compared.

Scenario 2 (harvesting) assumed that tree harvesting occurred within the coniferous forest of Camp Shelby at a rate defined as normal management by the Black Creek Ranger District (Department of the Army 1991). Tree harvesting of merchantable logs was restricted to the clear cutting of the oldest age class first and occurred at the historical average rate of approximately 14,750 thousand board feet (MBF) per year from 1990 to 2040. This represented a carbon loss of 6.6 Gg-C yr^{-1} with a harvested area of 93 ha yr^{-1}. Scenario 2 assumed that only the bole was carried off-site for the production of lumber and that all woody debris remained on-site. A conversion factor of 0.4 was used to calculate the carbon benefit of the off-site, wood-products pool created from the harvested trees (Heath and Birdsey 1993, Turner et al. 1993). Natural tree regeneration occurred after harvesting.

Scenario 3 (biofuel) assumed that trees were harvested to support a biofuel program as proposed for many DOD installations by the American Forestry Association (1992). Tree harvesting was restricted to the coniferous forest; however, no harvesting other than for

biofuel occurred. The clearcut harvest was 25,000 MBF per year and occurred on 98 ha yr^{-1} using the oldest age class first. This represented an annual carbon loss from the tree pool of 11.2 Gg-C yr^{-1}. Scenario 3 differs from scenario 2 in that 80% of aboveground tree biomass was collected for fuelwood production with 20% woody debris left on site. An efficiency factor of 0.9 was used to calculate the off-site carbon benefit of generating energy from the wood biomass instead of from fossil fuel (Sampson et al. 1993). Scenario 3 assumed natural tree regeneration after harvesting.

Scenario 4 (deforestation) assumed that tree removal from 8,593 ha (1,368, 948 MBF) was necessary to develop new training areas and corridors with the establishment of new maintenance facilities during the 1990s (Department of Army 1991). For this simulation, the coniferous forest was clear cut from 1900 to 1999 and 8,390 ha were seeded to grass while 203 ha were paved for roads or received some type of permanent construction facility. No other harvesting of trees occurred during the simulation. These trees were commercially harvested; therefore, only the boles were removed off-site (61.3 Gg-C yr^{-1}) and all slash was burned. A conversion factor of 0.4 was used to calculate the carbon benefit of the off-site, wood-products pool created from the harvested trees (Heath and Birdsey 1993, Turner et al. 1993). The soil carbon was maintained throughout the simulation at 80% for forestland converted to grasslands and 50% for forestland converted to permanent structures.

Scenario 5 evaluated the affect of reforestation on carbon sequestration. This scenario assumed that 4,050 ha of land that had been previously clearcut for military training or had been commercially harvested (Department of the Army 1991) were reforested during the 1990s at the ATLAS full stocking rate and composition consistent with a coniferous forest within the Black Creek Ranger District. During the 1980s, 4,505 ha of coniferous forest were developed for tracked vehicle maneuvering. For the purposes of this scenario, 3,590 ha were assumed to have been cleared of timber for development and available for reforestation. In addition, from 1986 to 1990, 460 ha of coniferous forest were commercially harvested with the land available for reforestation. Under this scenario, no trees were harvested between the years 1990 to 2040.

These five scenarios are management options that could occur at Camp Shelby, as well as many other DOD installations. Tree harvesting (scenario 2) and reforestation (scenario 5) are normal management practices at Camp Shelby (Department of the Army 1991). The biofuel (scenario 3) program is proposed by the AFA (1992) to reduce CO_2 emissions and reduce overall energy costs on many DOD installations. This scenario differs from scenario 2 in that the carbon of the harvested trees is returned immediately to the atmosphere through fuel combustion. This is considered to be a carbon benefit because the carbon released during combustion has been recently sequestered by the growing trees and no net carbon is released to the atmosphere. On the other hand, the combustion of fossil fuels releases carbon into the atmosphere that has been stored in an inert form for thousands of years. Proposed improvement of training facilities would result in tree removal on some forestland (scenario 4) with the conversion to grassland and the thinning of additional forest stands to allow for the maneuvering of tactical vehicles (Department of the Army 1991). Under this scenario, the management plan would be to harvest and

thin forest stands as required for the training area development and reduce or eliminate harvesting in other areas so as to not increase total forest harvests. Carbon sequestration occurs in grass swards and associated soils but at a much lower rate in comparison with forest trees and soils (Barker et al. 1995).

3.3 Results

Scenario 1 - No-Action Management

Forest carbon pools - 1990. The total carbon stored in the forests of Camp Shelby in 1990 was calculated to be 9,048 Gg-C (Gg=10^9 g, Figure 7). The majority of carbon resided in the coniferous forest (80%) because of its large land area. The deciduous and mixed forests stored 8 and 12% of the total carbon, respectively. Average carbon storage per unit area for the three forests was approximately 19 kg-C m^{-2}.

The distribution of carbon among the forest components varied considerably (Figure 8). Approximately 48% of all carbon resided in the tree pool which included living leaves, woody material, and coarse roots. The second largest carbon pool was the soil at 38%. Carbon storage within the forest floor, understory vegetation, and woody debris pools was 5, 1, and 8%, respectively. The partitioning of carbon among the five carbon pools was almost identical across forest types (Table 3). The main differences were in the tree and woody debris pools.

Forest carbon pools - 2040. The carbon pool for Camp Shelby forests increased steadily from 1990 to 2040 because of the growing trees. The total carbon pool in the year 2040 was calculated to be 10,981 Gg-C (Figure 7). The distribution of carbon among the three forests was the same as in 1990. Carbon storage per unit area averaged 22 kg-C m^{-2}.

The distribution of carbon among the various pools was similar as in 1990 in that the tree and soil dominated (Figure 9). However, the proportion of carbon in the tree pool increased to 53% while the soil pool decreased to 31% of total carbon. The forest floor, understory, and woody debris pools jointly represented 16% of total carbon.

The distribution of carbon within the various pools varied by forest type, but was partitioned similarly as in 1990 (Table 4). However, for all forest types the proportion of carbon within the tree pool increased with a proportional decrease in soil carbon. The carbon stored within the woody debris, forest floor, and understory pools were essentially the same as in 1990.

Carbon flux. During the 50-year simulation, there was a net flux of 1933 Gg-C into the Camp Shelby forests. Total carbon flux into the forest was the greatest during the first decade and then decreased somewhat linearly through the fifth decade (Figure 10). This pattern of carbon flux resulted from the rapid growth of the young forest stands during the first portion of the simulation and increased respiration as the stands matured. Without tree harvesting and the subsequent establishment of seedlings, the rate of forest-stand growth decreased along with net carbon gain as the forest matured.

The majority of carbon during the simulation was sequestered by the tree pool which increased in size by 36% and was consistently a carbon sink. The forest floor and woody

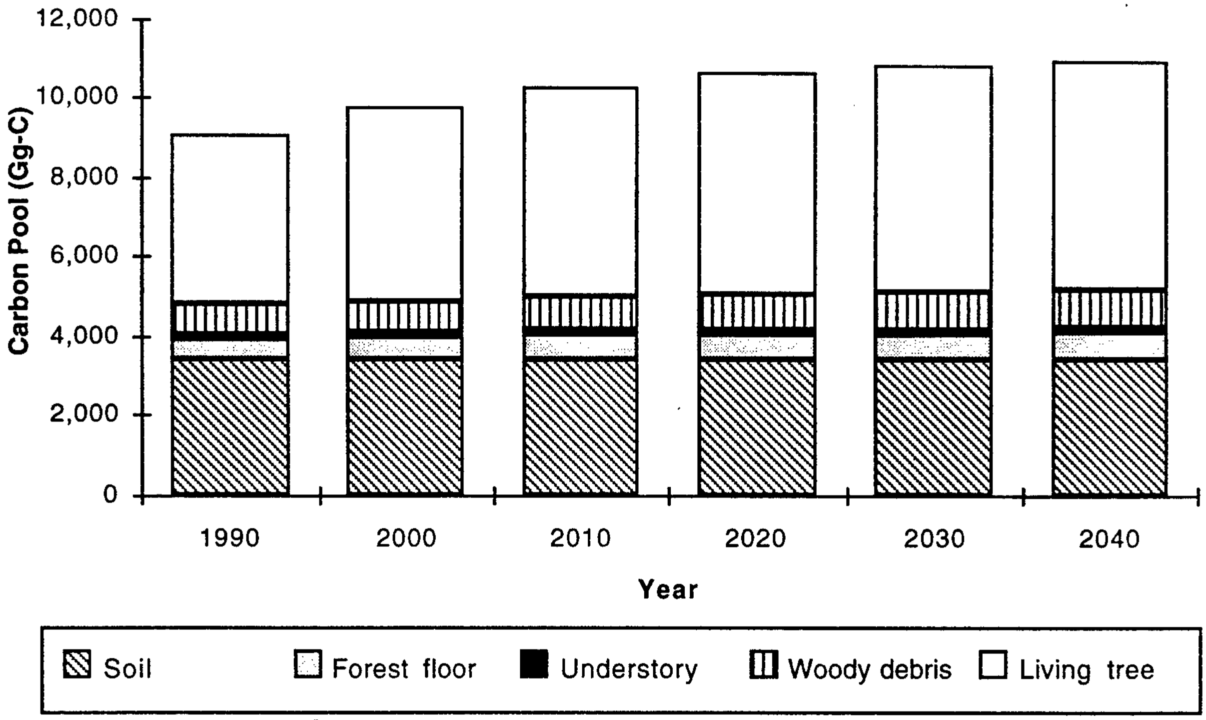


Figure 7. Projections of carbon pools for Camp Shelby forests under the no-action scenario.

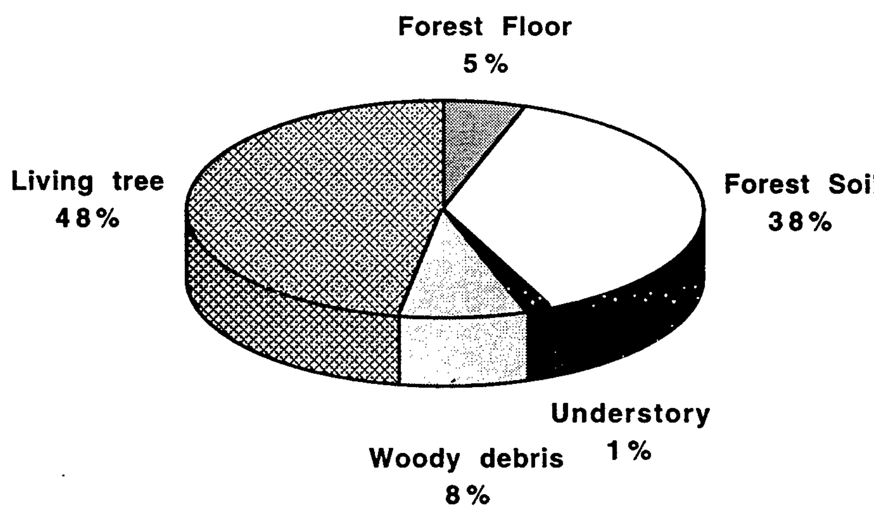


Figure 8. The modeled partitioning of carbon among the various pools of the forests of Camp Shelby in 1990 under the no-action scenario.

Table 3. Percent of total carbon within the various carbon pools by forest type for 1990 under the no-action scenario.

	Forest Type		
Carbon Pool	Coniferous	Deciduous	Mixed
Tree	46	51	49
Soil	38	39	39
Understory	2	1	1
Forest floor	5	4	4
Woody Debris	9	5	7

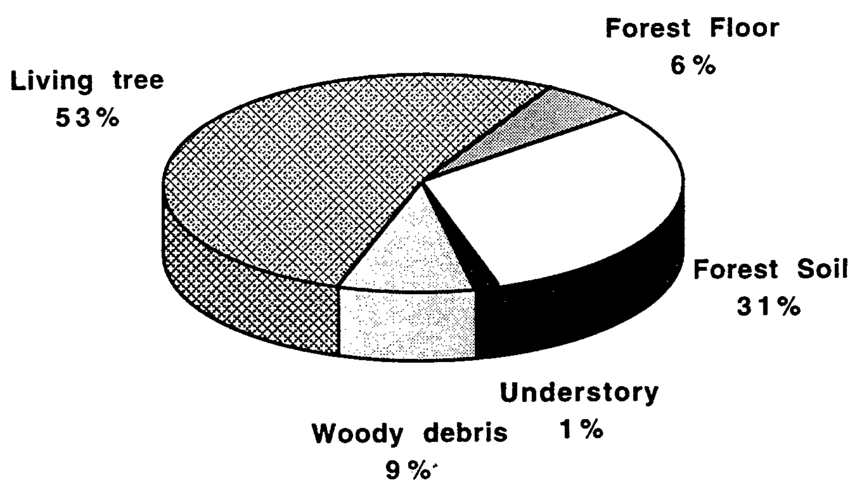


Figure 9. The modeled partitioning of carbon among the various pools for Camp Shelby forests in the year 2040 under the no-action scenario.

Table 4. Percent of total carbon within the various carbon pools per forest type for the year 2040 under the no-action scenario.

	Forest Type		
Carbon Pool	Coniferous	Deciduous	Mixed
Tree	52	58	56
Soil	31	31	32
Understory	1	1	1
Forest floor	6	5	5
Woody Debris	10	5	7

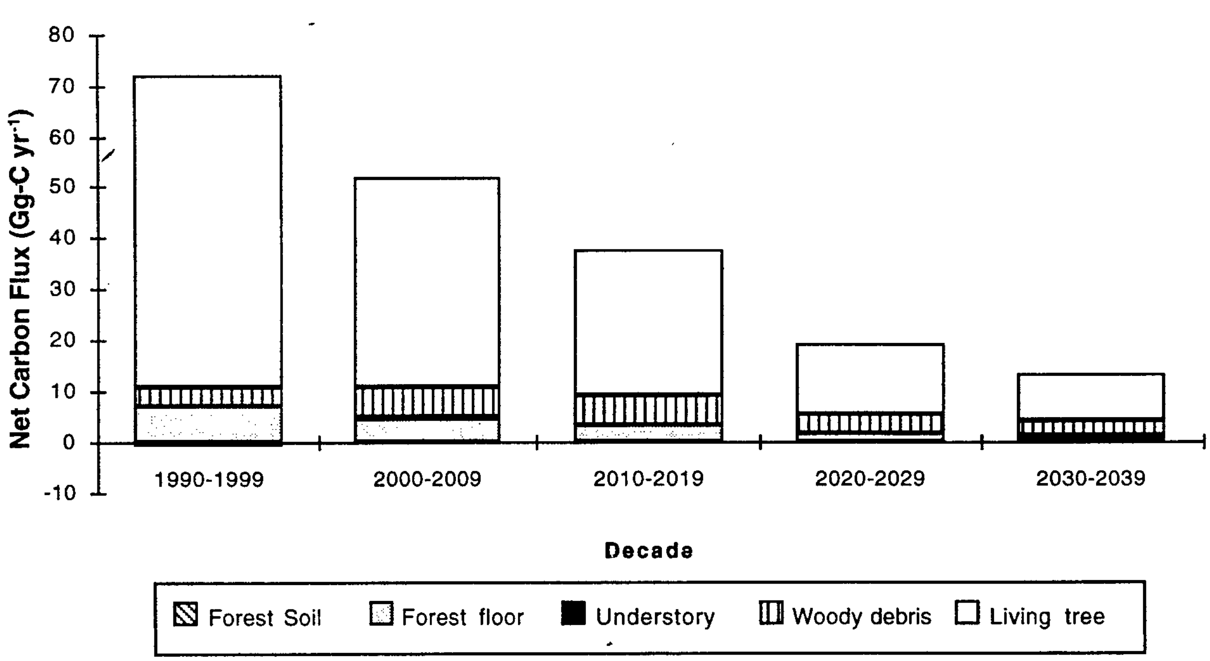


Figure 10. The modeled average annual carbon net flux projections by decadal intervals (e.g., 1990-1999 = average annual carbon flux for the years 1990 through 1999) for the forest of Camp Shelby assuming no-action management. Positive and negative values are respectively net carbon gains or losses.

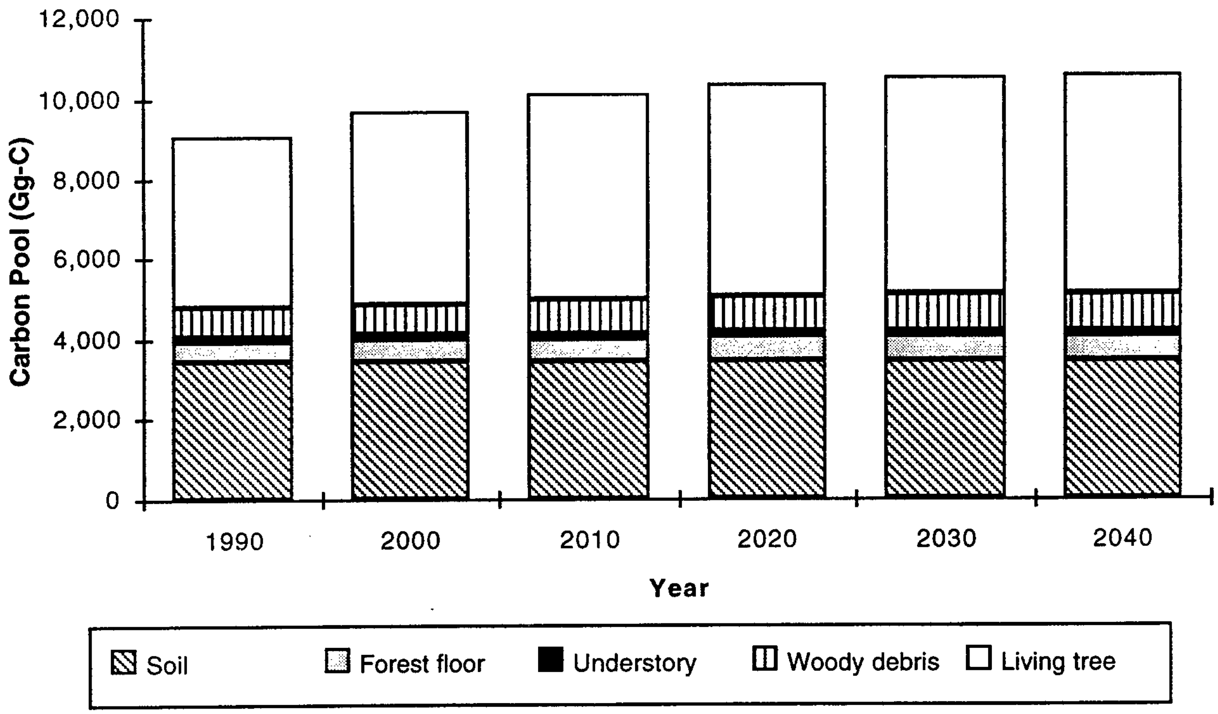


Figure 11. Projections of carbon pools for Camp Shelby forests under the harvesting scenario.

debris pools were also carbon sinks and increased by 39 and 30%, respectively. The understory vegetation was a small carbon source during the first 10 years, and thereafter a sink with an overall decrease of approximately 2%. Competition for sunlight, soil water, and soil nutrients between the trees and understory vegetation resulted in the latter being a carbon source during the first decade when the former were rapidly growing. As the forest stands matured, the tree canopy opened with the death of some trees which, in turn, allowed the understory vegetation to grow and become a carbon sink.

The 50-year average net carbon sequestration of the Camp Shelby forests was 39 Gg-C yr^{-1}. Total carbon sequestration by the coniferous, deciduous and mixed forests averaged 31, 3, and 5 Gg-C yr^{-1}, respectively. The rate of carbon sequestration per unit area averaged 79, 87, and 89 g-C m^{-2} yr^{-1} for the coniferous, deciduous, and mixed forests, respectively.

Scenario 2 - Tree Harvesting

Forest carbon pools - 2040. The total carbon pool for Camp Shelby forests with tree harvesting was 10,617 Gg-C in 2040 (Figure 11). The partitioning of carbon among the three forest types and among the five carbon pools by forest type was essentially the same as in scenario 1. Apparently, the rate of tree harvesting was not sufficient to adversely affect the partitioning of carbon among the various pools. Carbon storage per unit area averaged 21.6 kg-C m^{-2}.

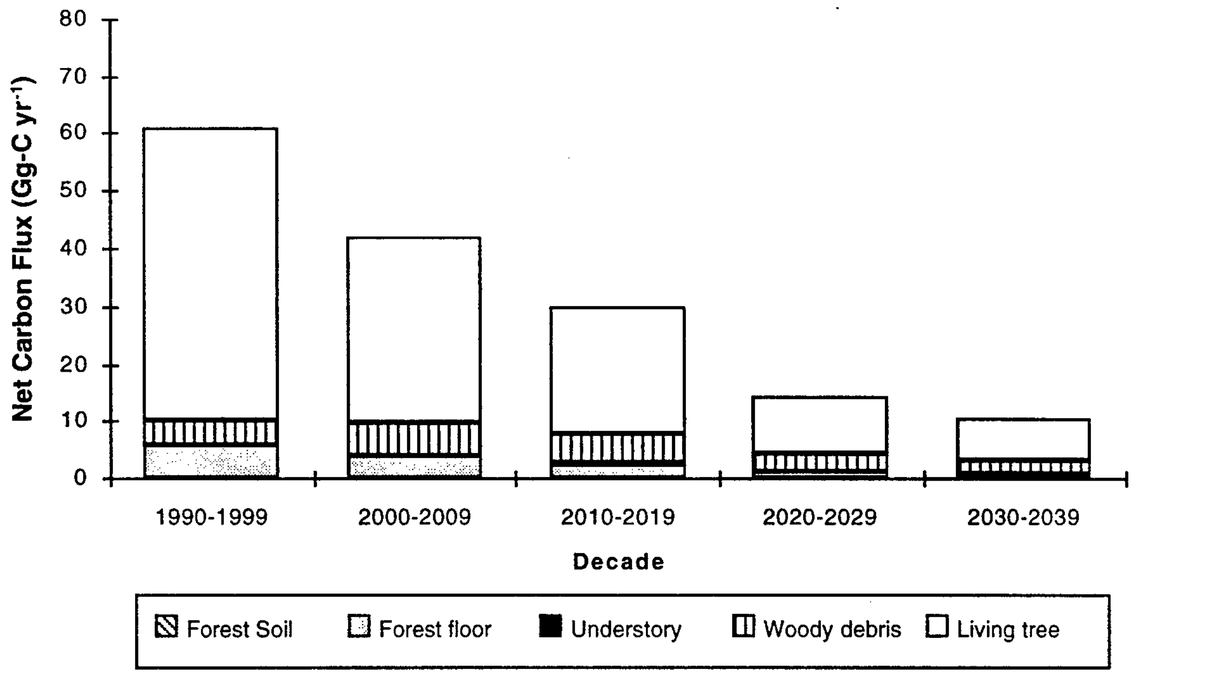


Figure 12. The modeled average annual carbon flux projections by decadal intervals (e.g., 1990-1999 = average annual carbon flux for the years 1990 through 1999) for the forests of Camp Shelby under the harvesting scenario. Positive and negative values are respectively net carbon gains or losses.

Carbon flux. The impact of tree harvesting on carbon dynamics is the immediate removal of carbon from the tree pool. However, the loss of carbon is offset by the concurrent growth of trees in non-harvested forest stands and the subsequent establishment and growth of seedlings from natural regeneration on the harvested land. Consequently, the net decrease in sequestration of carbon in the tree pool resulting from harvesting during the 50-year simulation was 113 Gg-C in comparison to the no-action scenario and 364 Gg-C for all pools combined.

During the 50-year simulation from 1990 to 2040, there was a net carbon flux of 1,569 Gg-C into the Camp Shelby forests. This is 19% less in net carbon gain compared with scenario 1. Total carbon flux into the forest was the greatest during the first decade and then decreased somewhat linearly through the fifth decade (Figure 12). This pattern of carbon flux resulted from the rapid growth of the young forest stands during the first portion of the simulation. As the forest stands matured, the rate of tree growth declined. The tree pool was the strongest carbon sink throughout the simulation and increased by 29%. The forest floor and woody debris pools were also carbon sinks and increased in size by 30 and 27% respectively. Once again, the understory pool was a carbon source during the first decade and then a small carbon sink for the remaining time.

The calculated 50-year net annual carbon gain for the Camp Shelby forests averaged 31 Gg-C yr^{-1}. Averaged carbon sequestration by the coniferous, deciduous and mixed forests was 23, 3, and 5 Gg-C yr^{-1}, respectively. The rates

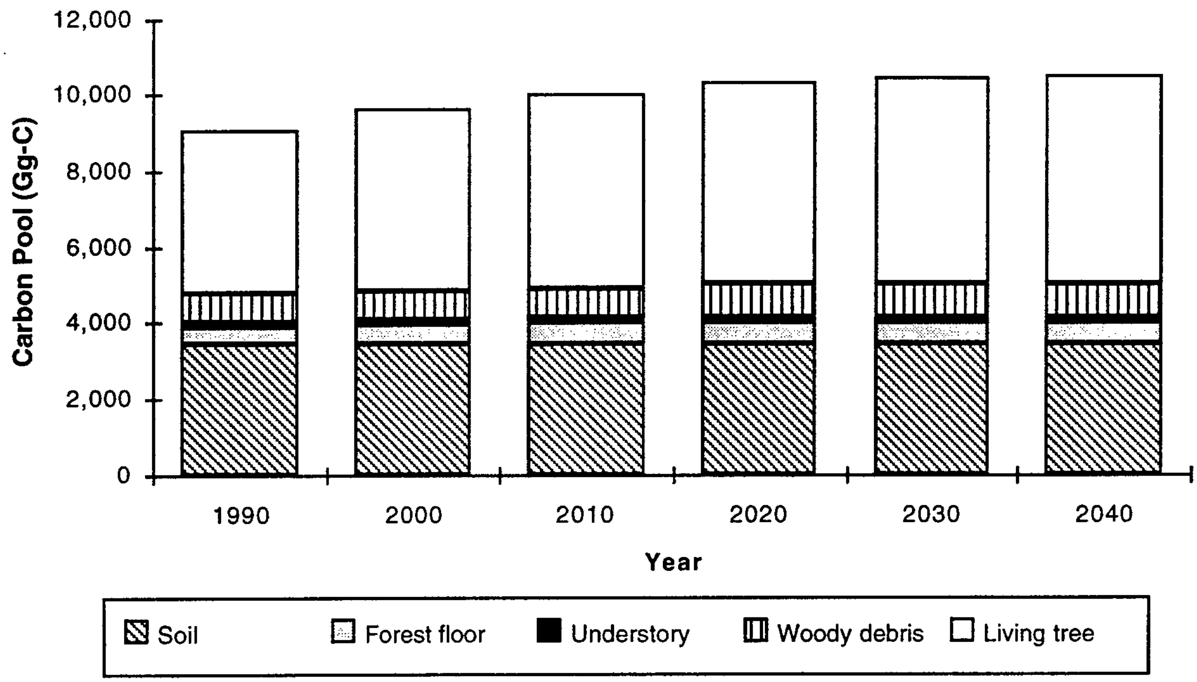


Figure 13. The modeled projections of carbon pools for Camp Shelby forests under the biofuel scenario.

of carbon sequestration per unit area for the coniferous, deciduous, and mixed forests were 58, 87, and 89 g-C m^{-2} yr^{-1}. The rate of carbon sequestration in the coniferous forest decreased by 25% in comparison with scenario 1.

Scenario 3 - Biofuel

Forest carbon pools - 2040. The total carbon pool for Camp Shelby forests after yearly tree harvesting to support a biofuels program in 2040 was 10,530 Gg-C (Figure 13). The partitioning of carbon among the coniferous, deciduous and mixed forests was respectively 79, 8 and 13%. The distribution of carbon within the various pools by forest type for the deciduous and mixed forests was essentially the same as scenario 1.

Carbon flux. The goal of tree harvesting to support a biofuel program is to offset carbon emissions from fuel combustion through carbon sequestration by the establishment and growth of new trees. The ideal situation would be where carbon emission from burning fuel-wood equals carbon sequestration by the forest. Tree harvesting to support the biofuel program resulted in the immediate loss of carbon from the tree pool. This loss, however, was partially offset by the growth of new seedlings on the harvested land. The net decrease in carbon sequestration in the tree pool during the 50-year simulation in comparison to scenario 1 was 326 Gg-C and 451 Gg-C for all pools combined.

During the 50-year simulation, there was a net flux of 1,482 Gg-C carbon into the Camp Shelby forests. This is a 23% loss in net carbon gain in comparison with scenario 1.

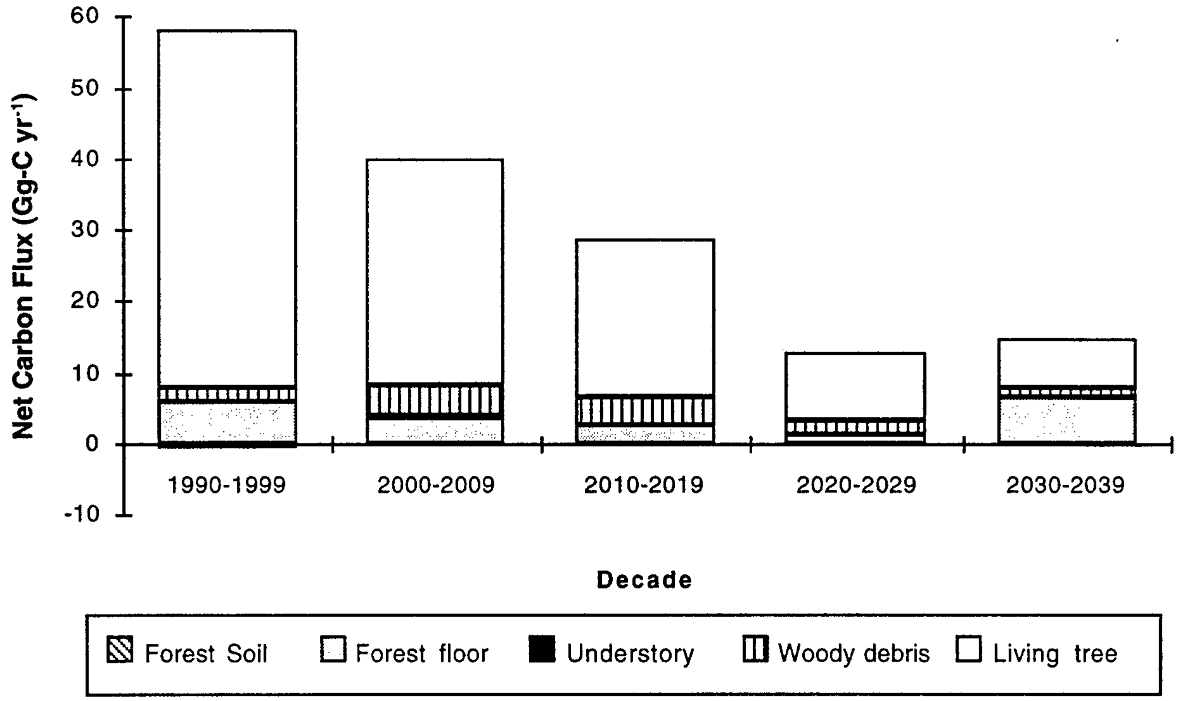


Figure 14. The modeled average annual carbon flux projections by decadal intervals (e.g., 1990-1999 = average annual carbon flux for the years 1990 through 1999) for the forests of Camp Shelby under the biofuel scenario. Positive and negative values are respectively net carbon gains or losses.

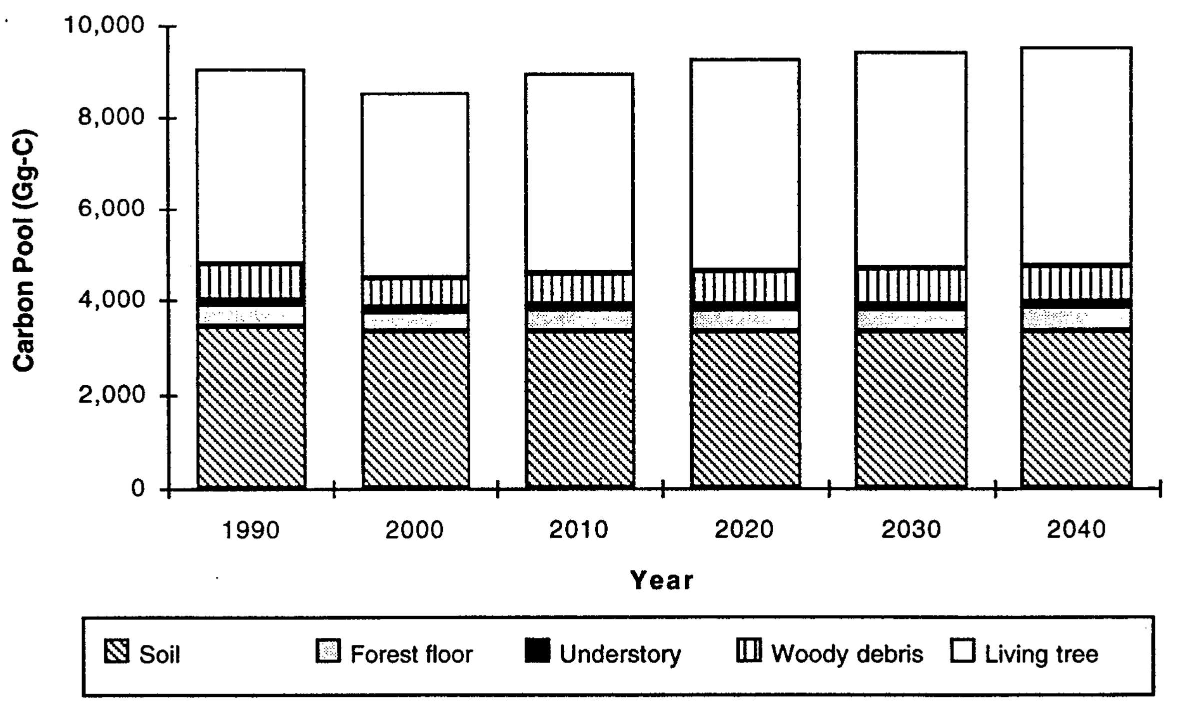


Figure 15. The modeled carbon pool projections for the forests of Camp Shelby under the deforestation scenario.

Carbon storage per unit area averaged 21 kg-C m^{-2} in 2040. The majority of carbon accumulation occurred in the tree pool which increased by 28% and was a carbon sink throughout the simulation (Figure 14). The forest floor and woody debris pools were also carbon sinks and increased in size by 30 and 18%, respectively. The understory pool was a carbon source during the first decade and then a carbon sink thereafter.

The 50-year average net carbon gain for Camp Shelby forests was 30 Gg-C yr^{-1}. Carbon sequestration by the coniferous, deciduous and mixed forests averaged 22, 3, and 5 Gg-C yr^{-1}, respectively. The rates of carbon sequestration for the coniferous, deciduous, and mixed forest averaged 55, 87, and 89 g-C m^{-2} yr^{-1}. The rate of sequestration for the coniferous forest was 27% less in comparison with scenario 1.

Scenario 4 - Deforestation

Forest carbon pools - 2040. The overall carbon pool for Camp Shelby forests after deforestation of 8,593 ha of coniferous forest was calculated to be 9,533 Gg-C in 2040 (Figure 15). The partitioning of carbon among the coniferous, deciduous, and mixed forests was 72, 9, and 14%, respectively. This represents an 8% decrease for the coniferous forest and a 2 and 1% increase for the deciduous and mixed forests, respectively, in comparison with scenario 1. The distribution of carbon among the five carbon pools varied slightly compared with scenario 1. The most significant changes were in tree carbon that changed from 53% to 50% and soil carbon that increased from 31% to 35%. The partitioning of carbon by pool and forest type was similar to the no-action scenario.

Carbon flux. Deforestation resulted in all pools being a carbon source during the first decade when the land-use change occurred (Figure 16). The tree pool was the largest source in decade 1, but recovered quickly in the second decade to be a carbon sink for the remainder of the simulation. Tree carbon in 2040 was 996 Gg-C less than in scenario 1 and total carbon was 1448 Gg-C less. Understory vegetation, woody debris, and forest floor also were carbon sinks for the remainder of the 50 years. The soil-carbon pool was carbon neutral for the remaining 40 years. The rate of carbon flux into the forests decreased linearly from decade 2 through decade 5. The loss of carbon in the tree pool was partially offset by concurrent tree growth in other forest stands. Tree seedling establishment did not occur because the deforested areas were seeded to grass or became roads and facility sites.

During the simulation period, there was a net carbon flux of 485 Gg-C into Camp Shelby forests, a 75% decrease in comparison with scenario 1. Carbon gain was the greatest in decade 2 and decreased with time due to a decrease in tree growth and increased respiration. The majority of carbon accumulation occurred in the tree pool which increased by 13%. The forest floor and woody debris pools also increased by 13 and 5%, respectively. The amount of carbon in the soil pool decreased by 4% in the first decade due to the conversion of the forestland to grassland and then remained constant for the remaining time. The understory pool was a carbon source the first two decades and a small sink the last three decades with a 19% decrease.

The 50-year average net carbon gain for Camp Shelby forests was 10 Gg-C yr^{-1}. Carbon sequestration by the coniferous, deciduous, and mixed forests averaged 1, 3, and 5 Gg-C yr^{-1},

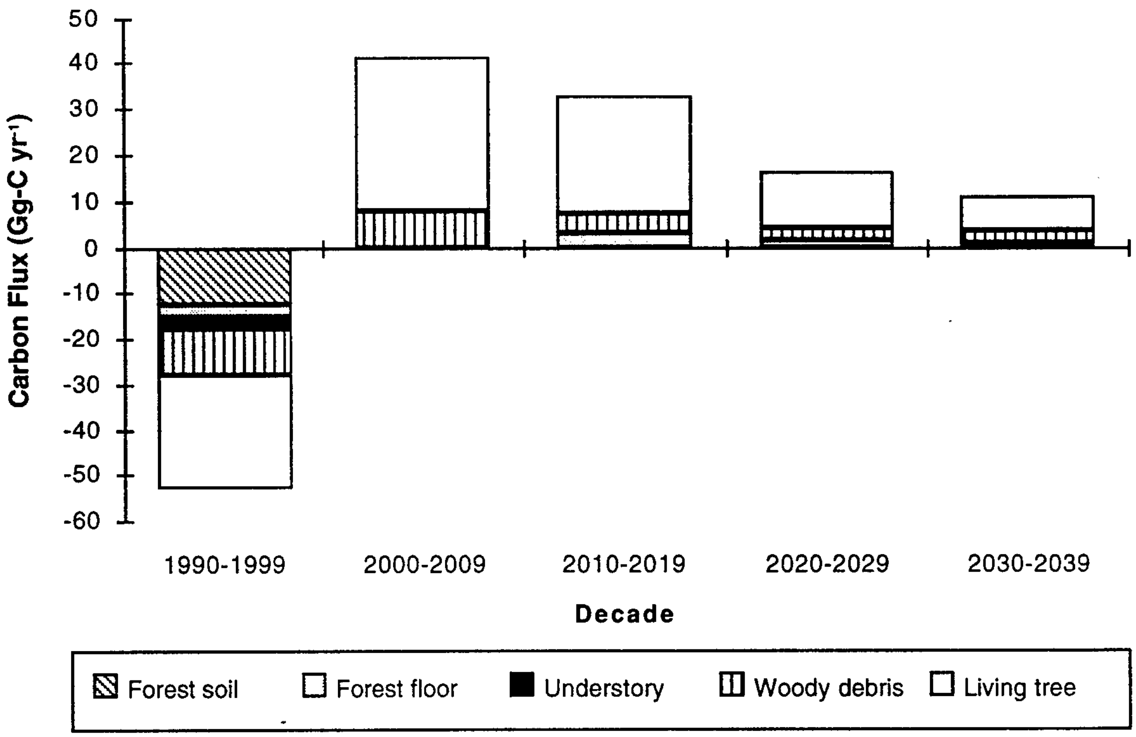


Figure 16. The modeled average annual carbon flux projections by decadal intervals (e.g., 1990-1999 = average annual carbon flux for the years 1990 through 1999) for the forests of Camp Shelby assuming the deforestation scenario. Positive and negative values are respectively net carbon gains or losses.

respectively. The rates of sequestration for the coniferous, deciduous, and mixed forest averaged 3, 87, and 89 g-C m^{-2} yr^{-1}. This is a 96% lower carbon sequestration rate for the coniferous forests as compared with scenario 1.

Scenario 5 - Reforestation

Forest carbon pools - 1990. The 1990 carbon pool under this scenario differs from that of the under scenario 1 because of the land (4,050 ha) that was reforested to coniferous forest. The additional land enrollment provided 141 Gg-C carbon to the 1990 soil pool that was not part of the assessment for the previous scenarios. We assumed that this additional land had negligible amounts of carbon in the tree and understory pools. Consequently, the 1990 non-soil carbon pools as described in scenario 1 are also applicable to this scenario. Thus, the 1990 carbon pool was 9,189 Gg-C for this scenario (Figure 17).

Forest carbon pools - 2040. The 2040 carbon pool for the forests of Camp Shelby after reforestation of 4050 ha was 11,737 Gg-C (Figure 17). The partitioning of carbon among the coniferous, deciduous, and mixed forests was 81, 7 and 12%, respectively. Average carbon storage for the coniferous, deciduous, and mixed forests was 22, 23, and 23 kg-C m^{-2}, respectively. Carbon storage for the coniferous forest was 3% less than in scenario 1 because of the young forest stands associated with the

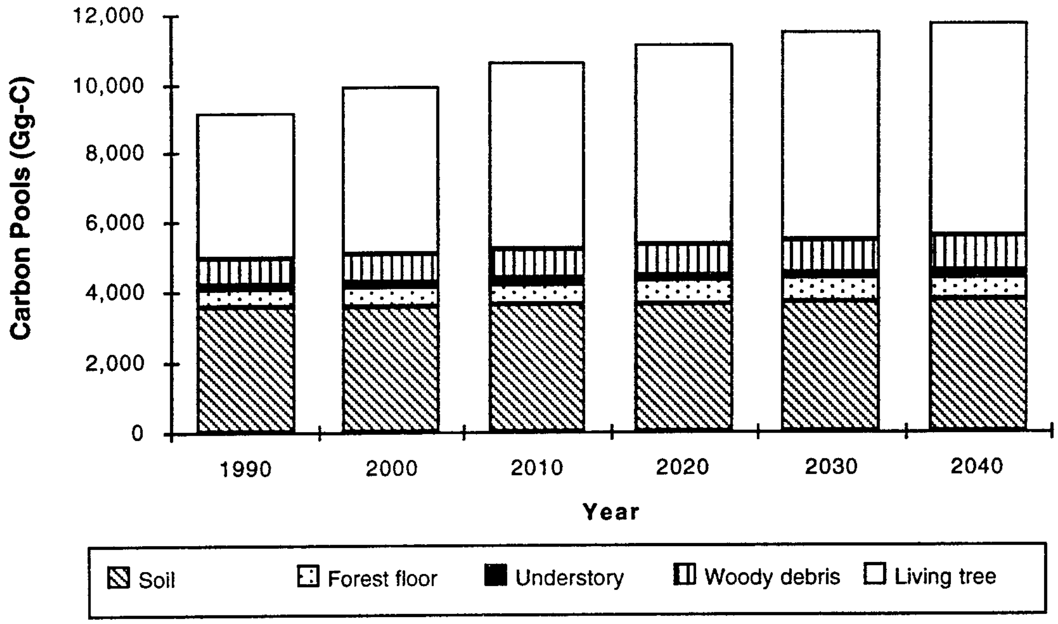


Figure 17. The modeled carbon pool projections for the forests of Camp Shelby assuming the reforestation scenario. New land enrollment provided an additional 141 Gg to the 1990 soil pool.

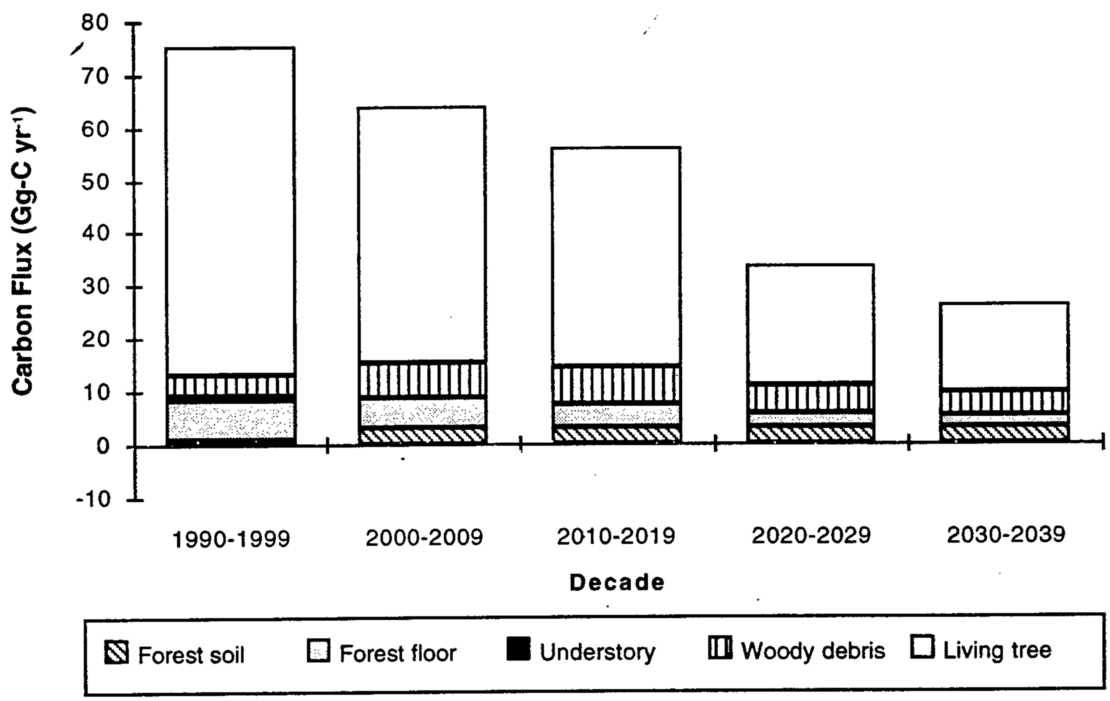


Figure 18. The modeled average annual carbon flux projections by decadal intervals (e.g. 1990-1999 = average annual carbon flux for the years 1990 through 1999) for the forests of Camp Shelby under the reforestation scenario. Positive and negative values are respectively net carbon gains or losses.

reforested land. The partitioning of carbon among the five pools was similar to scenario 1.

Carbon flux. Reforestation resulted in all pools being a carbon sink throughout the simulation (Figure 18). Carbon flux into the Camp Shelby forests was the greatest during decade 1 and decreased linearly through decade 5. Reforestation provided increased potential to sequester atmospheric carbon because of the rapid growth of the young trees. Consequently, average net sequestration of carbon by the tree pools was 377 Gg-C more than in scenario 1 and 615 Gg-C for all pools combined.

During the 50-year simulation, there was a net carbon flux of 2,548 Gg-C into the forests of Camp Shelby. This is a 32% increase in carbon sequestration in comparison with scenario 1. The majority of carbon accumulated in the tree pool which increased by 45%. In addition, the soil, forest floor, understory vegetation, and woody debris pools also increased their carbon storage by 4, 48, 6, and 36%, respectively. Unlike scenario 1, the understory vegetation was never a carbon source.

The 50-year carbon gain per annum for Camp Shelby forests averaged 51 Gg-C yr^{-1}. Carbon sequestration by forest was 43, 3, and 5 Gg-C yr^{-1} for the coniferous, deciduous, and mixed forests, respectively. The rates of carbon sequestration per unit area for the coniferous, deciduous, and mixed forests averaged 99, 87, and 89 Gg-C m^{-2} yr^{-1} The carbon sequestration rate for the coniferous forest was 29% higher than in scenario 1.

On-Site Carbon Benefit

According to the model simulations, tree harvesting whether for commercial, biofuel, or land-use change decreased carbon pools and the rate of carbon sequestration in comparison with no-action management, while reforestation increased carbon pools and sequestration (Figure 19). The pattern of carbon flux into the forest during the simulation was a decrease from one decade to the next as exemplified by the no-action scenario. The only exception to this pattern was the net flux of carbon to the atmosphere during the first decade under the deforestation scenario. Thereafter, net carbon flux was into the forest but at a much lower rate than the no-action scenario. The reforestation scenario also showed the same pattern of carbon flux as the benchmark, but at a much higher rate.

The no-action scenario provided a benchmark to compare the carbon sequestration of the other management scenarios (Table 5). Harvesting trees at a rate considered normal management by the Black Creek Ranger District could reduce on-site carbon sequestration by -8 Gg-C yr^{-1} for the 50-year period. Thus, this scenario is slightly carbon negative. In contrast, the deforestation scenario is decidedly carbon negative as it results in an average decrease in on-site sequestration of -29 Gg-C yr^{-1}. Reforestation is the only scenario that is carbon positive because average sequestration is increased by +12 Gg-C yr^{-1}.

Furthermore, the scenarios differ in the timing of their impacts on carbon sequestration. For example, the harvesting, biofuel, and deforestation scenarios have similar on-site carbon gains for the decade 2000-2009 (Table 5). However, for the entire 50-year period, the on-site carbon gains are more negative for defor-

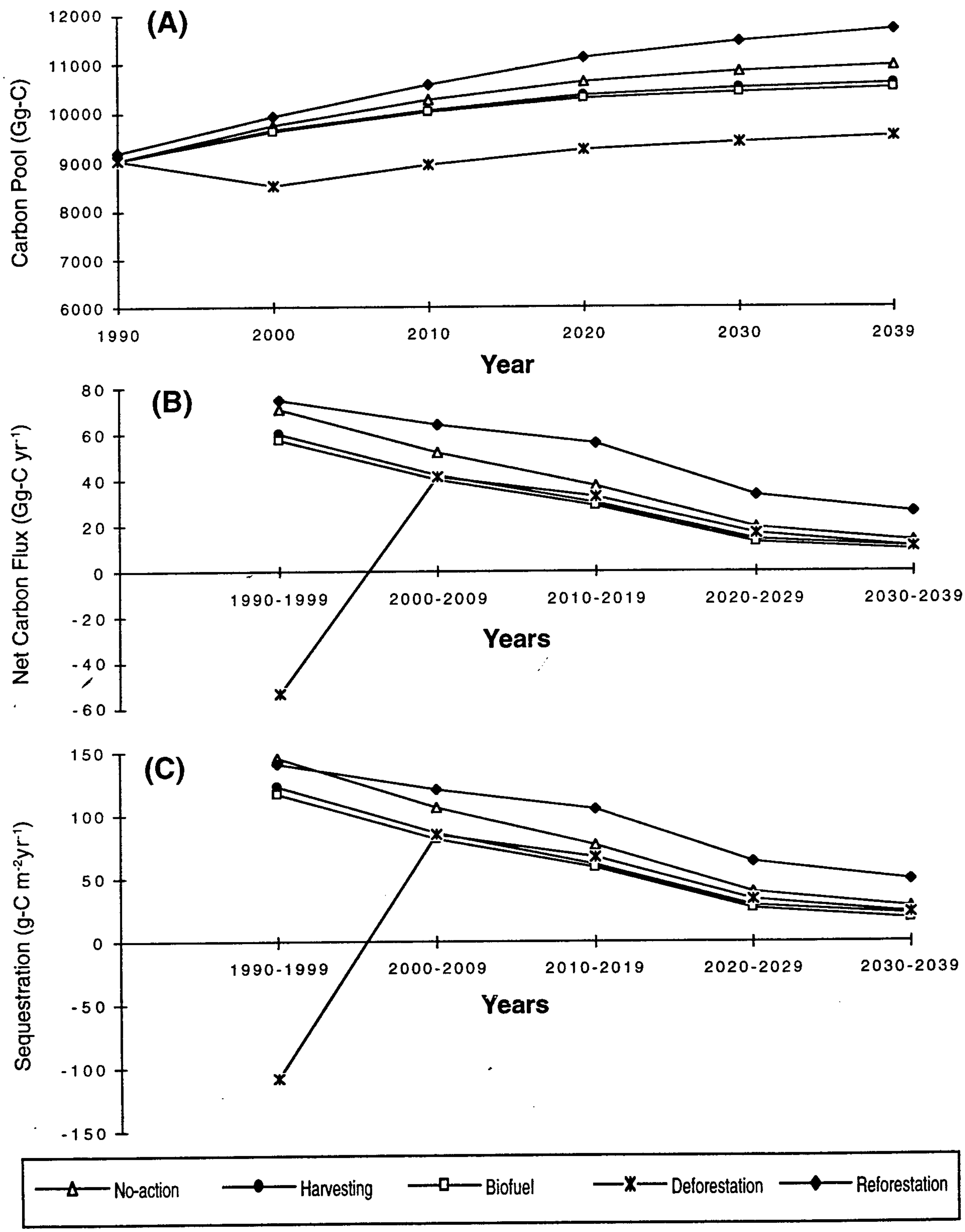


Figure 19. A comparison of (A) total carbon, (B) net carbon gain, and (C) carbon sequestration rate of Camp Shelby forests as influenced by five hypothetical management scenarios. Positive and negative values are respectively net carbon gains or losses.

Table 5. Carbon benefits of Camp Shelby forests during 10-year (2000-2009) and 50-year (1990-2039) periods as affected by five hypothetical management scenarios.

Management Scenario	Net On-site Carbon Sequestration		On-site Carbon Benefit[a]		Off-site Carbon Benefit[ab]		Combined Carbon Benefit[a]	
	(Gg-C yr^{-1})							
	10-year	50-year	10-year	50-year	10-year	50-year	10-year	50-year
No-action	52	39	0	0	0	0	0	0
Harvesting	42	31	-10	-8	2.6	2.6	-7.4	-5.4
Biofuel	40	30	-12	-9	10.1	10.1	-1.9	+1.1
Deforestation	41	10	-11	-29	12.2	4.9	+1.2	-24.1
Reforestation	64	51	+12	+12	0	0	+12.0	+12.0

[a] Compared with the no-action scenario.

[b] Assumes a 0.4 and 0.9 conversion efficiency to long-term wood products/landfill and biofuel energy production, respectively, for C transferred off-site.

estation than for the harvesting and biofuel scenarios. This reflects the primary loss of carbon sequestration potential by trees through the conversion of forestland to grassland.

The management scenarios are independent, and carbon gains (compared with the benchmark) change linearly with land area. Thus, it is possible to estimate carbon gains for scenario combinations for the forests of Camp Shelby or other forests with similar mixes of tree species and stand-age distribution (Table 5). For example, combining reforestation with tree harvesting would result in a carbon gain of +4 Gg-C yr^{-1} for the 50-year period. Deforestation of 4,297 ha instead of 8,593 ha would be less carbon negative, resulting in a carbon gain of -14 Gg yr^{-1}. A concurrent program of deforesting 8,593 ha and reforesting 4,050 ha would be slightly carbon positive for the decade 2000-2009 and carbon negative for the 50-year period.

Off-site Carbon Benefit

Under the harvesting, biofuel, and deforestation scenarios, harvested wood was transferred off-site for production of lumber or fuelwood. Long-term wood products/landfill or fuelwood can offset atmospheric carbon emissions (Table 5). For example, under the harvesting scenario, merchantable logs (representing 6.6 Gg-C yr^{-1}) were removed off-site during the 2000-2009 decade. With the conversion of the wood into lumber, approximately 2.6 Gg-C yr^{-1} is placed into long-term storage and kept out of the atmosphere. Similarly, under the biofuel scenario, wood biomass (representing 11.2 Gg-C yr^{-1}) was removed off-site for fuelwood production during the 2000-2009 decade. This will offset 10.1 Gg-C yr^{-1} that would have been released into the atmosphere from fossil-fuel combustion. Biofuels contain carbon that has been recently removed from the atmosphere and will be returned upon combustion. However, fossil fuels store inert carbon that was sequestered thousands of years ago and upon

combustion releases this "new" carbon into the atmosphere. Thus, there is no not increase in atmospheric carbon with the use of biofuels, while the use of fossil fuels will increase atmospheric carbon.

3.4 Discussion of Simulation Results

The modeling simulation under the no-action scenario suggests that Camp Shelby forests are a net carbon sink. During the 50-year simulation, carbon accumulated into the tree, woody debris, and forest floor pools. The understory vegetation pool was a carbon source to the atmosphere during the first decade of the simulation but then became a small carbon sink. Tree harvesting had a modest effect on reducing carbon sequestration in comparison to the no-action scenario. On the other hand, the conversion of forestland to grassland resulted in a significant flux of carbon to the atmosphere and also reduced the potential for future carbon sequestration. Reforestation significantly improved the long-term carbon sequestration potential.

Carbon Pools

Turner et al. (1993) show that the forests of the FS South Central region (in which Camp Shelby is located) are second only to the Northeast region in the amount of total carbon accumulation because of the large land area. Their estimate of current carbon storage in the forests of the South Central region is 6.7 Pg-C. However, Turner et al. (1993) found that the average quantity of carbon per unit area for the South Central region was the lowest in the United States at approximately 14.5 kg-C m^{-2}. The highest region was the Pacific Northwest West at approximately 33 kg-C m^{-2}.

Our estimate of carbon storage per unit area for Camp Shelby forest in 1990 was 19.0 kg-C m^{-2}. The forests of Camp Shelby should be more productive than those elsewhere in the region because of favorable growing conditions such as abundant precipitation throughout the year (Department of the Army 1991). Potential carbon storage in the longleaf pine-slash pine forests that occur on DOD land was estimated to be 19 kg m^{-2} by the AFA (1992). The agreement in carbon storage between the AFA calculation and our independent analysis gives confidence to the modeling approach that we used.

Turner et al. (1993) also provided data to estimate the partitioning of carbon among the various pools for the forests of the South Central region. Their data show that the majority of carbon resides in the soil (50%) and within tree biomass (34%). The remaining carbon is found in woody debris (10%), forest floor (3%), and understory (2%). Our calculations of carbon partitioning within the forests of Camp Shelby suggest that approximately 52% of total carbon resides in tree biomass while soil stores 31%. Much of the land within Camp Shelby is protected from all or limited use by the general public because of the dangers associated with military training and the rate of tree harvesting is less than in the other forests of the region (Department of the Army 1991). Heath and Birdsey (1993) provide data that show 54% of forest stands on private lands in the region that includes Camp Shelby are less than 30 years old with the 25-year age class dominating. The age-class distribution of Camp Shelby forests is much older in that approximately 20% of forest stands are less than 30 years old while the 50-70 age class dominates (Table 3). Consequently, a relatively large amount of carbon has been stored in the tree pool.

Carbon Flux

Carbon flux into forests depends on stand age or disturbance regime. Net carbon flux is balanced through plant photosynthesis, plant respiration, and tissue decomposition (Houghton et al. 1993). A disturbance to the forest such as tree harvesting or tree blow down from strong winds produces considerable woody debris. Therefore, carbon flux to the atmosphere is high because of elevated rates of decomposition of woody debris. A young, rapidly-growing tree stand will sequester large amounts of atmospheric carbon. As the tree stand recovers from disturbance through seedling establishment and growth, the rate of carbon sequestration will exceed the rate of carbon emissions. As the stand matures, the rate of carbon sequestration approaches carbon loss to the atmosphere. Then as the stand continues to age carbon loss to the atmosphere, through elevated rates of respiration and woody debris decomposition, may exceed the rate of carbon sequestration. However, carbon storage in an old tree stand is much greater than in a young tree stand.

Commercial- and biofuel-tree harvesting in this study had a modest effect on carbon sequestration in this modeling study. This occurred because of the concurrent growth of the non-harvested tree stands and the subsequent establishment and growth of seedlings on the harvested land. Also, only a relatively small proportion of the coniferous forest was harvested in any given year. A higher rate of harvesting would eventually result in the forest being a carbon source instead of a carbon sink as exemplified by the deforestation scenario.

Management Considerations

Management to sequester carbon should target long-term forest stand growth and productivity through ecosystem management as proposed by the Society of American Foresters (1993). Tree harvesting should be coupled with immediate reforestation or natural seedling establishment in a timely manner. However, if deforestation of large tracts of land is necessary for military training purposes, only the minimal area necessary for vehicle maneuvering should be clear cut. Where possible "islands" of trees should be left intact. The establishment of a vigorous grass cover on training areas that were deforested will improve carbon sequestration but at a much lower rate in comparison with forest stands (Barker et al., unpublished data). The grass cover will also help maintain soil carbon through the addition of biomass and erosion control. After training events, disturbed areas should again be reseeded to establish grasses as quickly as practical to maintain plant cover and reduce erosion. Finally, all lands that can support tree growth and will not interfere with training should be reforested.

The greatest carbon sequestration potential will come from rapidly growing tree stands. However, carbon storage is greatest in older tree stands. Therefore, a trade-off between sequestration and storage must be considered (Heath et al. 1993). Sustainable tree harvesting will reduce carbon sequestration by Camp Shelby forests compared with no harvesting. The reforestation of harvested stands can greatly increase carbon assimilation. Forest management to encourage carbon sequestration and conservation will provide other benefits such as improved wildlife habitat, decreased soil erosion, improved realism in military training, and improved overall environmental quality (American Forestry Association 1992).

Tree harvesting for lumber or fuelwood is advantageous to carbon sequestration and conservation (American Forestry Association

1992, Kauppi et al. 1992, Heath and Birdsey 1993, Kauppi and Tomppo 1993, Sampson et al. 1993). The lumber that is used in construction projects will still provide long-term carbon storage. Even when lumber is discarded to landfills it will retain its carbon for many more years while decomposition slowly occurs. Another advantage is that the establishment and subsequent growth of tree seedlings on the harvested land will sequester carbon at a much higher rate than older tree stands. However, harvesting old forest stands tends to create a long-term overall carbon source because of the release of carbon from decaying woody debris (Harmon et al. 1990).

Harvesting trees to support a biofuel program is advantageous to carbon sequestration in that fossil-fuel use is displaced with modern technology that can be more efficient and thus result in lower carbon emissions (Sampson et al. 1993, Wright and Hughes 1993). Also, the reforestation of the harvested land will sequester carbon released from combustion of the biofuel. Consequently, an equilibrium in carbon flux between the atmosphere and trees can be established as shown under the biofuel scenario.

Offsetting CO_2 Emissions

Total CO_2-C emissions for the State of Mississippi for 1990 were estimated to be 52,000 Gg-C (based on the 1985 emissions estimates of Piccot and Saeger [1990] plus a 1% yr^{-1} increase). If Mississippi were to adopt the CCAP target as a state goal, then 3640 Gg-C yr^{-1} in reduced CO_2 emissions or increased carbon sinks would be required.

For the decade 2000-2009, average net carbon flux into the Camp Shelby forests was calculated to be 52, 41, and 64 Gg-C yr^{-1} respectively under the no-action, deforestation, and reforestation scenarios (Table 5). The reforestation scenario would provide about 1.8% (0.3% above the no-action scenario) of the carbon offset needed to obtain the CCAP goal in Mississippi through carbon sequestration. In contrast, deforestation would reduce sequestration by 11 Gg-C yr^{-1}, and require additional offsets to attain the CCAP goal by the year 2000.

The carbon sequestration data for the reforestation scenario can be extrapolated to all national forests (403,225 ha) within Mississippi because of similarity in forest-stand age class distribution and composition with Camp Shelby forests (J. White, DeSoto National Forest, personal communication). Therefore, for the decade 2000-2009, a proactive reforestation program throughout the national forests in Mississippi at the same intensity as the reforestation scenario would sequester 122 Gg-C yr^{-1} more carbon in comparison with the no-action scenario. This would account for 3.4% of the CO_2-C offset needed to meet the CCAP goal within Mississippi.

The 50-year average flux provides a measure of the long-term implications of these management scenarios. Reforestation would, on average, increase sequestration by +12 Gg-C yr^{-1} compared to no management (Table 5). In contrast, deforestation would decrease average sequestration by -29 Gg-C yr^{-1}. Thus, over the long-term, these scenarios would either provide 0.3% of the required offset, or require an additional 0.8%, respectively.

4.0 DOD FOREST MANAGEMENT AND CARBON SEQUESTRATION

The research presented in Section 3 demonstrated that forest management can have both immediate and long-term consequences on atmospheric carbon sequestration. This section briefly presents management options that could improve the potential for atmospheric carbon sequestration by forests on DOD land with associated economic benefits.

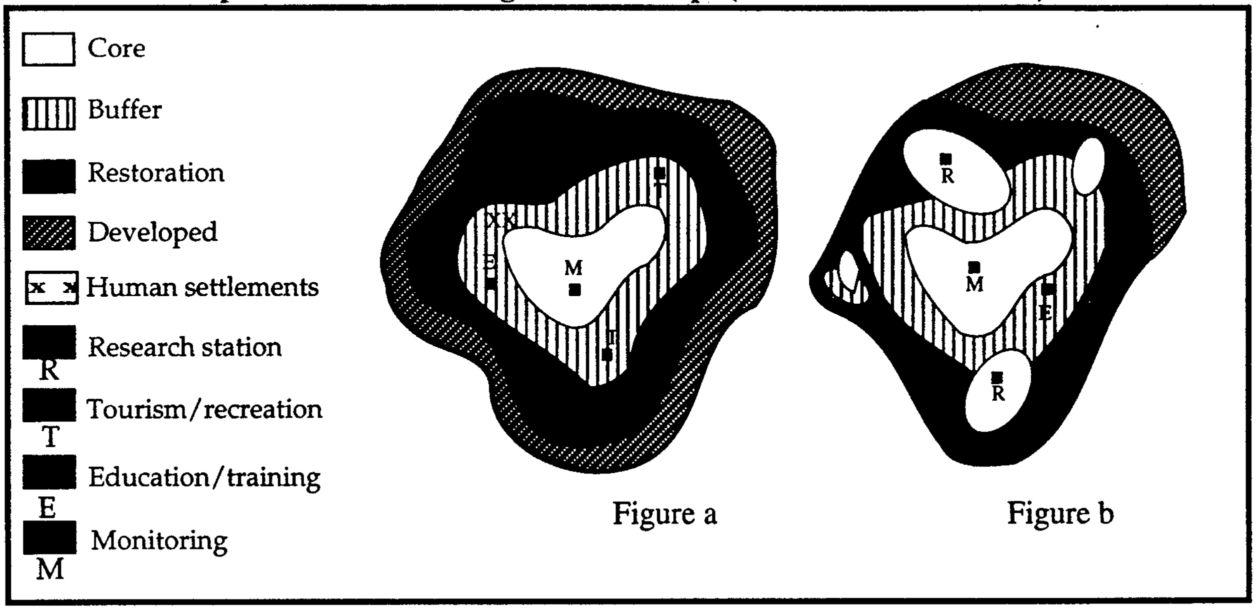
4.1. Management Practices for Carbon Sequestration

Conservation efforts through the ITAM program could be employed to sequester and conserve carbon in terrestrial ecosystems on DOD land. Most notably, proactive management should call for the reforestation of land degraded by training activities and improved land-use practices that would reduce further vegetation and soil destruction. The biosphere reserve concept is one approach to forest management that has been implemented successfully in many parts of the world and perhaps may be of promise on DOD forestland (Box 3). The biosphere reserve concept helps preserve primary forests while integrating multiple use endeavors into surrounding lands. Impact areas and sensitive wildlife habitat on DOD land could serve as the core area that receives the maximum protection. The buffer zone would be reserved for military training that results in minimal environmental damage. The restoration zone would be those areas recovering from environmental degradation. Finally, the developed zone could contain the cantonment facilities and other intense training areas. Of course, the biosphere reserve concept would have to be adapted to the unique needs of each installation.

Cantonment areas include administrative, housing, maintenance, medical and other support facilities. These areas are usually landscaped with grass, shrubs, and trees. Semi-developed areas include airfields, hangars, equipment storage, transportation and utility corridors, and other modified areas. These lands receive periodical mowing and woody plant control treatments. Unimproved lands include maneuver areas, buffer strips, drop zones, firing ranges, and ammunition impact areas and are generally left in natural vegetation. Unimproved lands are frequently managed for timber production or are grazed by livestock.

All land-use areas can be managed to increase the potential for carbon sequestration and reduce energy costs by the appropriate planting of trees and shrubs (U.S. Environmental Protection Agency 1992, Sampson 1993). Minimizing soil erosion will also improve carbon sequestration potential on these areas. The management strategy in cantonment areas should be to use trees and shrubs to beautify, reduce heating and cooling costs, and store carbon. Wind breaks have been shown to significantly reduce heating costs and also reduce CO_2 emissions while the trees sequester atmospheric carbon. Playgrounds, parks, and other recreational areas could benefit from landscaping with trees and shrubs to provide shade. Soil carbon sequestration and storage can be enhanced through maintaining plant cover, irrigation, and fertilization (Johnson 1992). Woody vegetation on the semi-developed sites should be allowed to grow if it does not present a safety hazard or interfere with normal, daily activities. Areas that require mowing or herbicides to control plant size and growth could be planted with trees and shrubs capable of growing within the plant size restriction. Unimproved lands offer the greatest opportunity for carbon sequestration by

Box 3. The Biosphere Reserve Management Concept (from Dixon et al. 1991).



The origin of Biosphere Reserves can be traced to the mid 1970s and UNESCO's Man and the Biosphere Program (MAB). However, the concept has evolved from one aimed at preserving a worldwide network of areas for basic ecological research, to one where development and management of the surrounding region is viewed as essential to the maintenance of the preserve area. Three specific management objectives are implicit in this concept: (1) habitat preservation (providing protection of genetic resources on a worldwide basis), (2) logistical coordination (interconnected facilities for research and monitoring), and (3) sustainable development of a range of economically viable and sustainable options for rural peoples living in proximity to the preserves) (Batisse 1980, 1990).

Four Major Zones

Miller (1978) identifies four major zones which should be in each biosphere reserve: The protected core serves as the baseline or scientific study area and includes the most pristine habitat in the region. This zone must be as large as possible to permit natural ecosystem functioning and is generally surrounded by a buffer zone in which limited anthropogenic activities can be permitted as long as they do not compromise the ecological integrity of the core. Resource extraction, tourism and other forms of resource conversion can be undertaken under strict controls. Often the buffer zone is adjacent to restoration zones, areas which have been severely altered but for which management is being intensified as a means of contributing to the sustained and economically viability of the region. Finally, there are the developed zones, including villages and related infrastructure.

In theory, each reserve has all four zones forming a gradient of management intensities aimed at protecting the ecological structure and function of the core (Figure a). The management of the entire region would ideally respond to a unified management structure and be protected by national law. In practice however, it seldom works out that way, due to the scarcity of natural habitat, existing management and jurisdictional structures and boundaries, established land use patterns, etc. (Figure b). In fact, most of the initial reserve "designations" were in existing protected areas. Professor Batisse claims this was initially seen as a "quality label", providing additional prestige or clout in the scientific-political arena. Today there are some 285 reserves in 72 countries representing a range of scale, ecological importance, management objectives and success (Batisse 1990, MacKinnon et al. 1986).

The major obstacles to proper management of biosphere reserves are not technical or scientific but managerial and institutional (Batisse 1990). Perhaps the real importance of the biosphere reserve concept is that it helps focus the issues involved in collaborative management of a natural resource base. Many groups, including the Department of Regional Development and Environment of the Organization of American States, The Nature Conservancy, Conservation International and others, have tested and improved upon the basic MAB model and achieved definitive results in both preservation of habitat and resource management for economic development.

vegetation and soil. Silvicultural practices could be used to improve stand tree productivity such as the control of understory vegetation and maximizing stem density. Reforestation of degraded lands would greatly improve the potential for carbon sequestration in addition to providing soil erosion control and improve wildlife habitat quality and recreational opportunities. Maintenance of vegetation will also enhance the carbon sequestration of soil.

Another management option for DOD installations that would provide a carbon-sequestration benefit is the establishment of a biofuel program (American Forestry Association 1992, Sampson 1993). The biofuel philosphy is that the carbon emitted from fuel combustion is sequestered by growing trees and other vegetation. Then the biomass is harvested and becomes the biofuel. Tree seedlings are then planted to take the place of the harvested vegetation. Thus, an equilibrium between carbon emissions and sequestration is established with no net loss of carbon to the atmosphere. Another benefit of a biofuel program is the displacement of fossil fuels which results in less carbon emissions into the atmosphere using biomass-energy technology (Wright and Hughes 1993).

4.2 Carbon Sequestration and Economic Benefits for DOD Installations

Proactive management of DOD forests can have immediate and long-range carbon and economic benefits. According to the American Forestry Association (1992) some of the advantages are:

- Proactive management of 193,548 ha of underutilized forestland could result in the sequestration of 50 to 60 Mg per acre of carbon over the next 40 years.
- Proactive management on approximately 354,839 ha of forestland could result in a net return of $200 million by 2032.
- Lumber is a form of long-term carbon storage that may be kept indefinitely in building structures or land fills and will only return carbon to the atmosphere upon decomposition or burning.
- Establishing or expanding biofuel programs on many military bases could result in a 10-year savings of up to $600 million and a 40-year savings of $1.8 billion and significantly reduce carbon emissions to the atmosphere.
- Landscaping with trees and shrubs in cantonment areas can significantly reduce heating and cooling costs, reduce carbon emissions, and sequester large amounts of atmospheric carbon.
- Improve recreational areas and wildlife resources by increasing vegetation cover, improving habitat and water quality, decreasing soil erosion and increasing soil carbon.
- Tree and shrub plantings around fuel and ammunition storage areas can improve overall safety by absorbing the impacts of explosions.
- Tree and shrubs plantings around target ranges and artillery impact areas would decrease the frequency of accidents by stopping stray bullets and flying shrapnel.
- Planting woody vegetation on runway and road medians, buffers, and approaches can reduce maintenance costs, reduce soil erosion, and improve overall safety.

5.0 SUMMARY AND CONCLUSIONS

The terrestrial biosphere is a significant component of the global carbon cycle. As such, forest vegetation and soil are important carbon pools. An understanding of changes in forest carbon dynamics as affected by land use is critical to predict changes in atmospheric CO_2 concentrations. Forests located on DOD training installations throughout the United States offer promising opportunities to sequester and conserve atmospheric carbon because reforestation opportunities, land-use practices, and large land tracts support mature forests that are vast carbon reservoirs. The influence of land-use practices such as tree harvesting, deforestation, and reforestation on carbon sequestration of Camp Shelby forests were evaluated through model simulations.

Carbon pools estimates of living tree, understory vegetation, soil, forest floor, and woody debris were based on Camp Shelby forest-stand area, age class, and stocking level. A stand-level carbon budget was developed for the coniferous, deciduous, and mixed forests based on growth and yield tables from the Aggregate Timberland Assessment System (ATLAS), a timber inventory model developed by the FS. Flux is the average annual change in the total carbon pool since the previous decade and was calculated by dividing the difference of the ending and beginning carbon pools by 10 years. Carbon pools and flux for five management scenarios were simulated from 1990 through 2040.

Forest management profoundly affected the carbon pools and sequestration potential of the forests. The no-action scenario provided the baseline for comparing harvesting, biofuel, deforestation, and reforestation scenarios. A general conclusion from the scenarios is that tree harvesting decreased carbon pools and sequestration rate and reforestation increased carbon pools and sequestration rate. Tree harvesting, even at the rate defined as normal management, resulted in a reduction in the total carbon pool and a 25% loss in the rate of carbon sequestration. Deforestation of 8,593 ha resulted in a dramatic reduction in total carbon and a 75% loss in on-site carbon sequestration potential. On the other hand, the reforestation of 4,050 ha of land significantly increased the carbon storage and resulted in a 31% increase in the rate of carbon sequestration. Thus, management practices that promote reforestation and discourage deforestation will provide the maximum carbon sequestration potential. In addition, other conservation benefits will include enhanced wildlife habitat, increased biodiversity, decreased soil erosion, and improved water quality.

Under the harvesting, biofuel, and deforestation scenarios, harvested wood was transferred off-site for production of lumber or fuelwood. Tree harvesting for lumber and other wood products is advantageous to carbon sequestration and conservation. The lumber that is used in construction projects will still provide long-term carbon storage. Even when lumber is discarded into landfills it will retain its carbon for many more years while decomposition slowly occurs.

Harvesting trees to support a biofuel program also provides a carbon benefit in that fossil fuel is displaced with modern, fuelwood technology that can lower carbon emissions. The ideal

situation is where carbon emissions from energy production approximates carbon sequestration by the trees that will eventually become fuelwood. Consequently, an equilibrium in carbon flux between energy production and tree sequestration is eventually established.

Under the CCAP, the United States is committed to reducing RITGs emissions to their 1990 levels by the year 2000. If Mississippi were to adopt the national target as a state goal, then 3,640 Gg-C yr^{-1} of emission reductions or offsets would be required. Reforestation of Camp Shelby could provide 0.3% of the

LITERATURE CITED

American Forestry Association. 1992. *Enhancing management of forests and vegetation on Department of Defense lands: Opportunities, benefits, and feasibility*. 230-R-005, US EPA Office of Planning and Evaluation, Washington, DC.

Apps, M.J. and W.A. Kurz. 1991. Assessing the role of Canadian forests and forest sector activities in the global carbon balance. *World Resources Review* 3:333-344.

Barker, J.R., G.A. Baumğardner, D.P. Turner, and J.J. Lee. 1995 (in press). Potential carbon benefits of the Conservation Reserve Program in the United States. *Global Ecology and Biogeography Letters*.

Barker, J.R., S. Henderson, R.F. Ross, and D.T. Tingey. 1991. Biodiversity and human impacts. P 353-361 In: W.A. Nierenberg (ed.), *Encyclopedia of Earth System Science*, Vol. 1, Academic Press, Inc., San Diego, CA.

Batisse, M. 1980. The relevance of MAB. *Environmental Conservation* 7:179-184.

Batisse, M. 1990. Development and implementation of the biosphere reserve concept and its applicability to coastal regions. *Environmental Conservation* 17:111-116.

Bazzaz, F.A. 1990. The response of natural ecosystems to the rising global CO_2 levels. *Ann. Rev. Ecol. Syst.* 21:167-196.

Birdsey, R.A. 1992. *Carbon storage and accumulation in United States forest ecosystems*. General Technical Report WO-59, US Department of Agriculture Forest Service, Washington, DC.

Boden, T.A., R.J. Sepanski, and F.W. Stoss. 1991. *Trends '91: A compendium of data on global change*. Publ. No. ORNL/CDIAC-46, Oak Ridge National Laboratory, Oak Ridge, TN.

Clinton, W.J. and A. Gore. 1993. The climate change action plan. The White House, Washington, DC.

Cole, C.V., K. Flach, J. Lee, D. Sauerbeck and B. Stewart. 1993. Agricultural sources and sinks of carbon. *Water, Air and Soil Pollution* 70: 111-122.

Cost, N.D., J.O. Howard, B. Mead, W.H. McWilliams, W.B. Smith, D.D. VanHooser, E.H. Warton. 1990. *The biomass resource of the United States*. General Technical Report WO-57, US Department of Agriculture Forest Service, Washington, DC.

Cubbage, F.C. 1992. Federal land conversion programs. P 177-194 In: R. N. Sampson and D. Hair (eds.), *Forests and Global Change*, Vol. 1, American Forests, Washington, DC.

Davis, M.B. and C. Zabinski. 1992. Changes in geographical range resulting from greenhouse warming: Effects on

biodiversity in forests. P 297-308 In: R.L. Peters and T.E. Lovejoy (eds.), *Global Warming and Biological Diversity*. Yale University Press, New Haven, CT.

Department of the Army. 1991. Military training use of national forest lands, Camp Shelby, Mississippi. Draft Environmental Impact Statement, Vol. 1, National Guard Bureau and Mississippi Army National Guard.

Dixon, R.K. and D.P. Turner. 1991. The global carbon cycle and climate change: Responses and feedbacks from below-ground systems. *Environmental Pollution* 73:245-262.

Dixon, R.K., P.E. Schroeder, and J.K. Winjum (eds.). 1991. *Assessment of promising forest management practices and technologies for enhancing the conservation and sequestration of atmospheric carbon and their costs at the site level.* EPA/600/3-91/067, US EPA Environmental Research Laboratory, Corvallis, OR.

Dixon, R.K., J.K. Winjum, and P.E. Schroeder. 1993. Conservation and sequestration of carbon: The potential of forest and agroforest management practices. *Global Environmental Change* 40:159-173.

Dixon, R.K., S. Brown, R. A. Houghton, A.M. Solomon, M.C. Trexler, and J. Wisniewski. 1994. Carbon pools and flux of global forest ecosystems. *Science* 263:185-190.

Franklin, J.F., F.J. Swanson, M.E. Harmon, D.A. Perry, T.A. Spies, V.H. Dale, A. McKee, W.K. Ferrell, J.E. Means, S.V. Gregory, J.D. Lattin, T.D. Schowalter, and D. Larsen. 1991. Effects of global climate change on forests in northwestern North America. P 7049-7962 In: G. H. Orians (ed.), *The Northwest Environmental Journal*, Institute for Environmental Studies, University of Washington, Seattle, WA.

Grabherr, G., M. Gottfried, and H. Pauli. 1994. Climate effects on mountain plants. *Nature* 369:448.

Grainger, A. 1991. Overcoming constraints on assessing feasible afforestation and revegetation rates to combat global climate change. In: D. Howlett and C. Sargent (eds.), *Proceedings of a technical workshop to explore options for global forest management.* International Institute for Environment and Development, London, UK.

Harmon, M. 1993. Woody debris budgets for selected forest types in the U.S. In: D.P. Turner, J.J. Lee, G.J. Koerper, and J.R. Barker (eds.). The Forest Sector Carbon Budget of the United States: Carbon Pools and Flux under Alternative Policy Options. EPA/600/3-93/093, US EPA Environmental Research Laboratory, Corvallis, OR.

Harmon, M.E., W.K. Ferrell, and J.F. Franklin. 1990. Effects on carbon storage of conversion of old-growth forests to young forests. *Science* 247:699-702.

Heath, L.S. and R.A. Birdsey. 1993. Carbon trends of productive temperate forests of the conterminous United States. *Water, Air, and Soil Pollution* 70:279-294.

Heath, L.S., P.E. Kauppi, P. Burschel, H-D. Gregor, R. Guderian, G.H. Kohlmaier, S. Lorenz, D. Overdieck, F. Scholz, H.

Thomasius, and M. Weber. 1993. Contribution of temperate forests to the world's carbon budget. *Water, Air, and Soil Pollution* 70:55-69.

Hinckley, D. and G. Tierney. 1992. Ecological effects of rapid climate change. P 291-300 In: S.K. Majumder, L.S. Kalkstein, B. Yarnal, E.W. Miller, and L.M. Rosenfeld (eds.), *Global climate change: Implications, challenges and mitigation measures*. The Pennsylvania Academy of Science.

Houghton, R.A., J.D. Unruh, and P.A. Lefebvre. 1993. Current land cover in the tropics and its potential for sequestering carbon. *Global Biogeochemical Cycles* 7:305-320.

IPCC (Intergovernmental Panel on Climate Change). 1990. *Scientific Assessment of Climate Change*. World Meteorological Organization/UN Environmental Program. Cambridge University Press, Cambridge, UK.

IPCC (Intergovernmental Panel on Climate Change). 1992. *Climate Change: Proceedings of a workshop on assessing technologies and management systems for agriculture and forestry in relation to global climate change*, Australian Government Publishing Service, Canberra, Australia.

Johnson, D.W. 1992. Effects of forest management on soil carbon storage. *Water, Air, and Soil Pollution* 64:83-120.

Kauppi, P.E. and E. Tomppo. 1993. Impact of forests on net national emissions of carbon dioxide in West Europe. *Water, Air, and Soil Pollution* 70:187-196.

Kauppi, P.E., K.K.K. Mielikäinen, and K. Kuusela. 1992. Biomass and carbon budget of European forests, 1971 to 1990. *Science* 256:70-74.

Kern, J.S. 1994 (in press). Estimation of soil water retention modeled from texture, organic matter, and bulk density. *Soil Science Society of America Journal.*

Kern, J.S. and M.G. Johnson. 1993. Conservation tillage and impacts on national soil and atmospheric carbon levels. *Soil Science Society of America Journal* 57:200-210.

King, G.A. 1993. Conceptual approaches for incorporating climatic change into the development of forest management options for sequestering carbon. *Climate Research* 3:61-78.

Lashof, D.A. and D.A. Tirpak (eds.). 1990. *Policy options for stabilizing global climate*. 21P-2003.1, Report to Congress. US EPA Office of Policy, Planning and Evaluation, Washington, DC.

Luxmoore, R.J., S.D. Wullschleger and P.J. Hanson. 1993. Forest responses to CO_2 enrichment and climate warming. *Water, Air and Soil Pollution* 70: 309-323.

MacKinnon, J., K. MacKinnon, G. Child and J. Thorsell (eds.). 1986. Managing protected areas in the tropics. International Union for the Conservation of Nature and Natural Resources, Gland, Switzerland.

Miller, K.R. 1978. Planning national parks for ecodevelopment: Methods and cases from Latin America. Center for Strategic Management Studies, School of Natural Resources, University of Michigan, Ann Arbor, MI.

Mills, J.R. and J.C. Kincaid. 1992. The aggregate timberland assessment system--ATLAS: a comprehensive timber projection model. General Technical Report PNW-GTR-281, U.S. Department of Agriculture Forest Service , Pacific Northwest Research Station, Portland, OR.

Moulton, R.J. and K.R. Richards. 1990. Costs of sequestering carbon through tree planting and forest management in the United States. General Technical Report WO-58, US Department of Agriculture Forest Service, Washington, DC.

Myers, N. 1992. Synergisms: Joint effects of climate change and other forms of habitat destruction. P 344-354 In: R.L. Peters and T.E. Lovejoy (eds.), Global Warming and Biological Diversity. Yale University Press, New Haven, CT.

National Academy of Science. 1991. Policy implications of greenhouse warming. National Academy Press, Washington, DC.

Neilson, R.P. 1993. Vegetation redistribution: A possible source of CO_2 during climatic change. *Water, Air, and Soil Pollution* 70:643-674.

Oechel, W. and B.R. Strain. 1985. Native species responses to increased carbon dioxide concentration. P 117-154 In: B.R. Strain and J.D. Cure (eds.), *Direct effects of increasing carbon dioxide on vegetation.* DOE/ER-0238, US Department of Energy, Washington, DC.

Peters, R.L. and J.D. Darling. 1985. The greenhouse effect and nature reserves. Bioscience 35:707.

Peters, R.L. and T.E. Lovejoy (eds.). 1992. Global Warming and Biological Diversity, Yale University Press, New Haven, CT.

Piccot, S., and M. Saeger. 1990. National- and state-level emissions estimates of radiatively important trace gases (RITGs) from anthropogenic sources. EPA-600/8-90-073. US EPA, Air and Energy Engineering Research Laboratory, Research Triangle Park, NC.

Plantinga, A.J., and R.A. Birdsey. 1993. Carbon fluxes resulting from U.S. private timberland management. *Climatic Change* 23:37-53.

Post, W.M., T-H Peng, W.R. Emanuel, A.W. King, V.H. Dale, and D.L. DeAngelis. 1990. The global carbon cycle. *American Scientist* 78:310-326.

Rubin, E.S., R.N. Cooper, R.A. Frosch, T.H. Lee, G. Marland, A.H. Rosenfield, and D.D. Stine. 1992. Realistic mitigation options for global warming. *Science* 257:148-149, 261-266.

Sampson, R.N. 1993. Forest management and biomass in the U.S.A. *Water, Air, and Soil Pollution* 70:519-532.

Sampson, R.N., and D. Hair (eds.). 1992. Forests and Global Change. Volume One: Opportunities for Increasing Forest Cover.

American Forestry Association, Washington, DC.

Schneider, S.H., L. Mearns, and P.H. Gleick. 1992. Four climate scenarios for impact assessment. P 38-58 In: R.L. Peters and T.E. Lovejoy (eds.). *Global Warming and Biological Diversity*, Yale University Press, New Haven, CT.

Schroeder, P.E., R.K. Dixon, and J.K. Winjum. 1993. Forest management and agroforestry to sequester and conserve atmospheric carbon dioxide. *Unasylva* 44:52-60.

Schwengals, P., B. Solomon, C. Ebert, J. Scheraga, M. Adler, D. Ahuja, J. Wells, S. Seidel, K. Andrasko, and L. Burke. 1990. Technical options for reducing greenhouse gas emissions. V1-V167 In: D.A. Lashof and D.A. Tirpak (eds.). 21P-2003.1. *Policy options for stabilizing global climate*, Report to Congress. US EPA Office of Policy, Planning and Evaluation, Washington, DC.

Shugart, H.H. 1993. Global Change. In: A.M. Solomon and H.H. Shugart (eds.). *Vegetation Dynamics & Global Change*, Chapman & Hall, New York, NY.

Simpson, L.G. and D.B. Botkin. 1992. Vegetation, the global carbon cycle, and global measures. P 411-425 In: D.A. Dunnette and R.J. O'Brien (eds.), *The Science of Global Change: The Impact of Human Activities on the Environment.* American Chemical Society, Washington, DC.

Smith, S.H. 1992. *United States forest response and vulnerability to climate change.* School of Forestry and Environmental Studies, Yale University, New Haven, CT. Report prepared for the Office of Technology Assessment, Washington, DC.

Smith, T.M. and D. Tirpak (eds.). 1989. *The potential effects of global climate change on the United States.* EPA-230-05-89-050, Report to Congress, US EPA, Office of Policy, Planning and Analysis, Washington, DC.

Smith, T.M. and H.H. Shugart. 1993. The transient response of terrestrial carbon storage to a perturbed climate. *Nature* 361:523-526.

Smith, T.M., H.H. Shugart, G.B. Bonan, and J.B. Smith. 1992. Modeling the potential response of vegetation to global climate change. *Advances in Ecological Research* 22:93-116.

Smith, T.M., W.P. Cramer, R.K. Dixon, R. Leemans, R.P. Neilson, and A.M. Solomon. 1993. *Water, Air, and Soil Pollution* 70:19-38.

Society of American Foresters. 1993. *Task force report on sustaining long-term forest health and productivity.* Society of American Foresters, Bethesda, MD.

Thompson, M.T. 1989. *Forest statistics for Georgia, 1989.* Resource Bulletin SE-109, US Department of Agriculture Forest Service, Washington, DC.

Trexler, M.C. 1991. *Minding the carbon store: Weighing US forestry strategies to slow global warming.* World Resource Institute, Washington, DC.

Turner, D.P., J.J. Lee, G.J. Koerper, and J.R. Barker (eds.). 1993. *The forest sector carbon budget of the United States: Carbon pools and flux under alternative policy options*. EPA/600/3-93/093, US EPA Environmental Research Laboratory, Corvallis, OR.

U.S. Army Corps of Engineers. 1989. *Integrated training area management*. Fact Sheet EN-13, U.S. Army Corps of Engineers, Construction Engineering Laboratory, Champagne, IL.

U.S. Environmental Protection Agency. 1992. *Cooling our communities*. 22P-2001, US EPA Office of Planning and Evaluation, Washington, DC.

Vogt, K.A., C.C. Grier, and D.J. Vogt. 1986. Production, turnover, and nutrient dynamics of above- and below-ground detritus of world forests. *Advances in Ecological Research* 15:303-377.

Volz, H., W.U. Kriebitzsch, and T.W. Schneider. 1991. Assessment of potential, feasibility and costs of forest options in the temperate and boreal zones. In: D. Howlett and C. Sargent (eds.). *Proceedings of a technical workshop to explore options for global forest management*. Bangkok, Thailand, April 24, 1991. International Institute for Environment and Development, London, UK.

Waring, R.H., and W.H. Schlesinger. 1985. *Forest ecosystems: Concepts and management*. Academic Press, Inc., Orlando, FL.

Webb, III, T. 1992. Past changes in vegetation and climate: lessons for the future. P 59-75. In: R.L. Peters and T.E. Lovejoy (eds.) *Global Warming and Biological Diversity*, Yale University Press, New Haven, CT.

Winjum, J.K., R.K. Dixon, and P.E. Schroeder. 1993. Forest management and carbon storage: An analysis of 12 key forest nations. *Water, Air, and Soil Pollution* 70:239-258.

Wisniewski, J., R.K. Dixon, J.D. Kinsman, R.N. Sampson, and A.E. Lugo. 1993. Carbon dioxide sequestration in terrestrial ecosystems. *Climate Research* 3:1-5.

Woodward, F.I. 1992. A review of the effects of climate on vegetation: Ranges, competition, and composition. P 105-123 In: R.L. Peters and T.E. Lovejoy (eds.). *Global Warming and Biological Diversity*. Yale University Press, New Haven, CT.

Woodwell, G.M. 1992. How does the world work? Great issues of life and government hinge on the answer. P 31-37 In: R.L. Peters and T.E. Lovejoy (eds.), Global Warming and Biological Diversity. Yale University Press, New Haven, CT.

World Resources Institute. 1990. World resources 1990-91. Oxford University Press, Oxford, UK.

Wright, L.L. and E.E. Hughes. 1993. U.S. carbon offset potential using biomass energy systems. *Water, Air, and Soil Pollution* 70:483-498.